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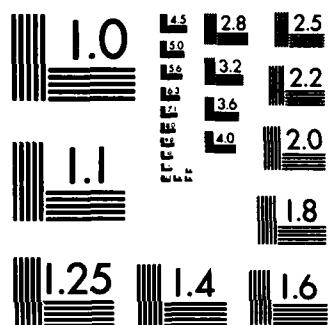
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May 1983

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EMC SYSTEM TEST AND ANALYSIS INTERFACE

The Boeing Company

E. F. Ball, L. Knutson and B. L. Carlson

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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, NY 13441

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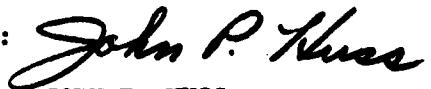
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One of the major problems in ensuring the electromagnetic compatibility (ECM) of a system is the efficient utilization of equipment level measurements and system level analysis tools. The contents of this report present an indepth evaluation of MIL-STD-461 and the Unites States Air Force's system level analysis tool, Intrasystem Electromagnetic Compatibility Analysis Program (IEMCAP). Recommended changes to improve system level EMC predictions based on equipment and system level test

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results are presented along with recommended changes to IEMCAP.

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EMC SYSTEM TEST & ANALYSIS INTERFACE

1.0 GENERAL

1.1 Introduction

The combination of several factors has caused a concern for the efficiency and effectiveness of analyses and tests for electromagnetic interference (EMI) and electromagentic compatibility (EMC).

a. Technical correlation between equipment test and system test specifications needs improvement.

b. Integrated circuit (IC) low power requirements, rapid response times, and nonlinear detection modes require expanded analytical and test methods.

c. IC functional and packaging densities have restricted test point accessibility and complicated parameter measurements even if instrumentation influences are not taken into account.

d. The preceding factors have generated a need for improved analytical methods capable of handling large scale, complex situations in an accurate and expedient manner. From this need for improved analytical methods a number of digital computer codes have evolved. Since these computer codes were subject to the same technical and cost constraints in the development of any functional system, they are sometimes unique, restrictively specialized, frequently of different program languages, and unevaluated on a large scale basis. The net result is a set of computer codes lacking the capacity to meet the overall EMC analysis needs of a system.

Recognition of these conditions established the following set of objectives discussed in this report.

1. Develop a methodology for efficient and effective system level EMC tests;

2. Develop equipment level tests supportive of system testing;

3. Recommend changes to improve system level EMC predictions based on equipment and system level test results;

4. Identify IEMCAP changes necessary to support items 1, 2, and 3;

5. Design records for an equipment and system EMC test data file,

6. Provide a discrepancy list identifying specification and documentation deficiencies relative to items 1 through 3.

1.2 Summary

The system test specification, MIL-E-6051 is deemed an uncomplicated but technically an effective document primarily because it makes no attempt to standardize test methods or results. On the other hand the test standards and absolute limits impose by MIL-STD-461 can be detrimental to efficiency and effectiveness unless the three, ne requirements of the B version are rigorously applied. These changes are:

a) Equipment test requirements and limits are to be tailored to suit the using syster requirements, the universal equipment application of the A version has been dropped;

b) Equipment susceptibility testing is to be performed to the threshold of malfunction or test equipment limits, this is critical to analyses as susceptibility thresholds are generally not available, particularly for abnormal conditions, except through MIL-STD-461 type of tests.

c) Exempting required or intentional emission limits has been dropped from the A version, this is consistent with the general MIL-E-6051 requirement that all functions must be compatible.

Tailoring MIL-STD-461 requirements is principally a prime contractor function with customer concurrence because subcontractors will seldom, if ever have the system knowledge necessary to establish limits. Tailoring is seen as an iterative process which will initially complicate the administration of contracts but will eventually more than offset incurred costs by increased technical effectiveness and efficiency.

Changes are recommended for some MIL-STD-461 tests and one new test is recommended. The greatest need for improvement involves digital circuits and their source and susceptibility characteristics.

Two topics intended to be tutorial in nature are the distinct, yet dependent, relationships between the management and technical aspects of implementing problem solutions, and the undue weight, cost, and reliability burdens EMC controls can impose on a system. Theoretically, EMC analyses should be equally exhaustive in keeping unjustified filters, excess wire and shields, etc., out of a design as that expended to get them in a design.

1.3 EMC Problem Philosophy

It is presumed every EMC problem contains a source(S) of interference, something which responds (R) to the interference, a coupling mode (C) between S and R, and the S,C,R relationship is expressable as

$$SC \gtrless R.$$

If the product is greater than R a problem exists and the EMC safety margin is negative. If the SC product is less than R there is no problem and the EMC safety margin is positive. If the problem is expressable, resolvable and each parameter controllable there is virtually an unlimited range of solutions. For example assume an assessment has yielded a -30 dB margin, the S:C:R relationship is limited only by the capability to control each of the parameters, i.e., S:C:R (dB) = 30:0:0, 15:15:0, 10:10:10,...,0:0:30. While any one parameter (S,C or R) can be used to attain a given margin, the EMC engineer is obligated to provide the widest range of feasible solutions and to avoid singular solutions. A program manager with alternative EMC problem solutions can optimize the EMC solution with other implementation considerations which involve cost, schedule, weight, reliability, logistics, etc. However, a singular solution will always limit the degree of optimization. EMC efficiency is therefore directly related to the ability to define and implement design changes.

Extending the S,C,R philosophy to the test aspect of the problem can be used to develop a set of guidelines and constraints.

1) The S:C:R relationship describes the state of the system.

   a) If all three parameters are known a complete assessment is possible.

   b) If only two parameters are known the assessment can only establish a limiting value for the third parameter.

   c) If only one parameter is known the assessment can establish a limiting value for the combination of the other two but cannot place restrictions on the individual parameters.

   d) Estimates, judgement and/or experience can be substituted for unknown parameters but an unknown error is introduced into the assessment.

2) The EMC state of the system is unique to the system under consideration.

   a) Sources have intrasystem origins such as power supplies or transmitters; or, intersystem origins such as remote radiation or lightning strokes.

   b) Responses are always within the system and represent the input-output characteristics of particular hardware.

   c) Coupling modes are system dependent and principally involve wiring networks and shielding.

   d) A system which performs its intended functions in the required environment(s) has an unassessed safety margin between 0dB and an unknown positive value.

3) Establishing the response characteristics of equipment generally requires test parameters involving the input power leads, signal input lead(s) and/or output lead(s). Appendix A contains a description of test methods typically used for obtaining impedance data at equipment ports. This type of testing is generally limited to controlled laboratory conditions because of the risk of equipment damage

and substantiates the need for MIL-STD-461 or similar tests. MIL-STD-461 does not presently contain tests to measure coupling characteristics and cannot be used for that purpose in its present form. MIL-STD-461 does provide for source characteristic measurements; however, unless radiated tests are performed in an anechoic room the data obtained can be misleading.

2.0 SITUATION OVERVIEW

This section contains discussions on some causes of system level EMC problems, test specification MIL-E-6051, test standard MIL-STD-461, and, the computer code Intrasystem Electromagnetic Compatibility Analysis Program (IEMCAP). The purpose of the discussions is to provide a summary of these EMC document contents and their pertinency to planning and performing meaningful EMI/EMC tests and analyses.

2.1 System EMC Problem Discussion

Electromagnetic compatibility (EMC) testing at the system level has one specific objective—verify that the system will function as intended and designed <u>within the constraints and limitations that are imposed on the system</u> but without adverse electromagentic interference effects (EMIE) or electromagnetic radiation effects (EMRE). Since the EMC test is performed at the integrated system level, it is the culmination of efforts that commenced in the earliest program phase; Figure 2.1 attempts to identify these efforts and their sequence. Testing must be based on the system configuration and to be effective and efficient must specifically address—

a. The functional and environmental constraints imposed on the system,

b. The mechanical and electrical design and layout of the system,

c. Access to and instrumentation of parameters to be measured,

d. Methods of minimum effect on the parameter being measured,

e. Cost effectiveness without technical sacrifice.

The order and incidence of EMC problems is believed to be as follows:

a. Power Distribution Network Problems - Transients associated with surge loading conditions and synchronous load rectification are estimated to cause 30 to 40% of all EMC problems. "Grounding" is included in this group because the "green wire", "safety wire", "instrumentation common", etc. is invariably a part of the power distribution network whether it is a primary, secondary, or conditioned power situation.

b. Integrated Circuit (IC) Susceptibility - The ever increasing susceptibility of the IC is rapidly becoming the number one EMC problem. The ability of a digital IC to switch

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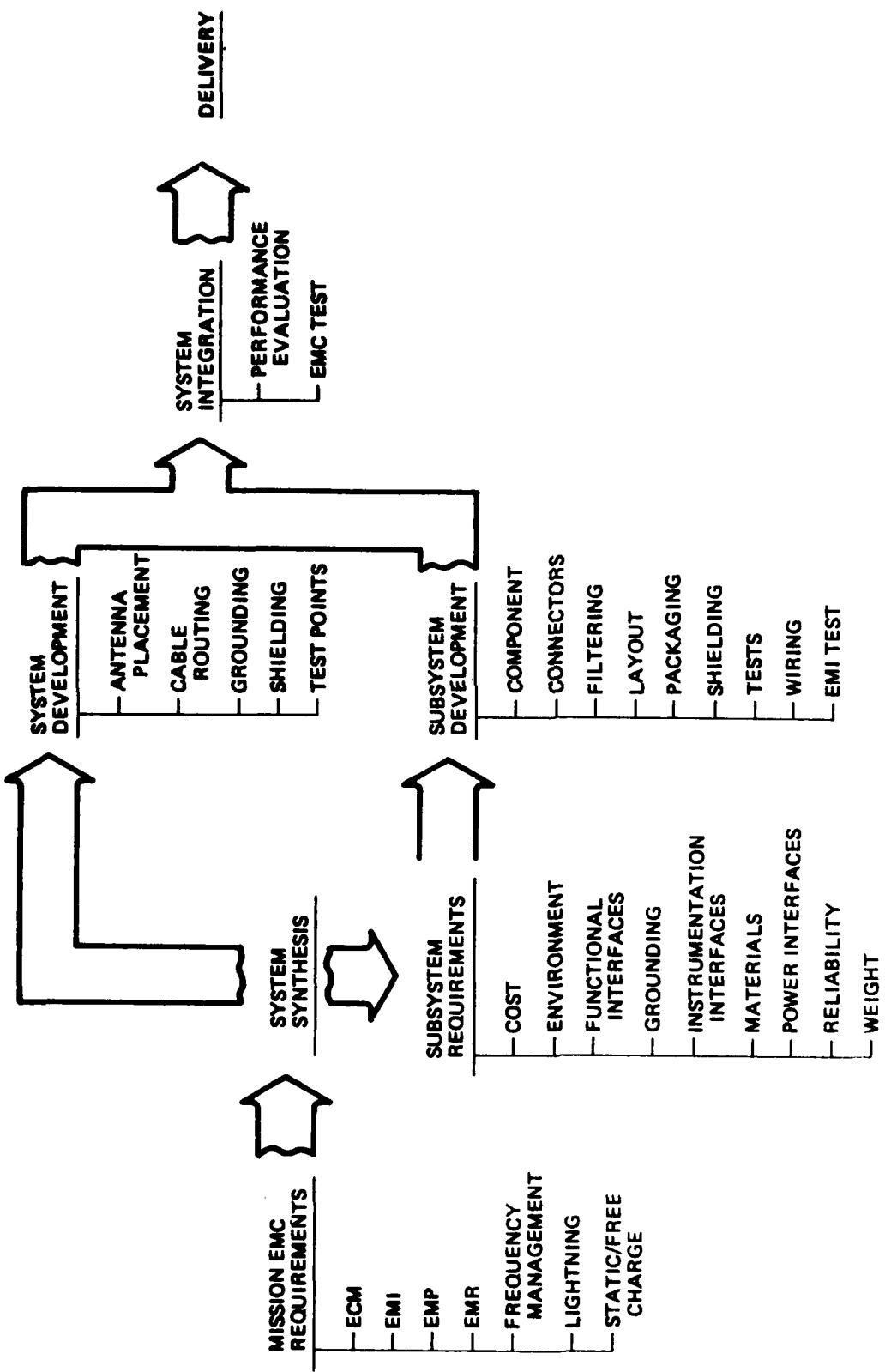
Figure 2.1: EMC Activities Related To A Typical Hardware System Procurement Cycle

and respond in less than 5 nanoseconds makes interwire coupling length of 1 to 3 meters a concern; this length can easily be either an interface or interface cabling distance. Most IC's, particularly the operational amplifier, are capable of detecting RF well above their normal mode frequency cut off. The IC-EMC problem percentage is estimated to be in the same percentage range as power network problems which is about 30 to 40%.

c.   Antenna to Antenna Coupling - This class probably represents less than 15% of system EMC problems but receives perhaps 75% of the attention devoted to solving these problems because the EMC discipline and specifications were founded for the protection of RF receivers. However, the RF community's spectrum management, antenna efficiency, band pass/band reject filtering, modulation techniques, etc., necessary to attain performance generally exceed the EMC community's capability to protect these receivers. Typically, the antenna-to-antenna problem class involves multipath effects or overlooked minor lobe effects because the true system geometry is never considered until the system is actually built; full scale simulations are seldom achieved.

Examples of the above problems and concerns are presented in the following subsections.

2.1.1 Intrasystem EMC Problem Characteristics

Figure 2.2 depicts a simple system containing a power supply (A), two functional loads (B&C), and necessary interconnections. A, B, and C are assumed to have been procured from separate subcontractors. The prime contractor's task is to judicially integrate them into a system and demonstrate required MIL-E-6051 EMC safety margins. The figure is annotated with two sets of equations labeled ideal and real. The ideal set is intended to reflect the subcontractor situation-an isolated subsystem developed using a dedicated laboratory power supply, simple system load simulators, and unrealistic system wires or cables. The real set is intended to reflect the reality of conditions that occur in the system. Equation 3 of the two sets will be discussed to illustrate the EMC concerns of an integrated system.

If the real and ideal equation sets are to be equal, then all the right hand members of the real set must be zero or combine in a manner to be zero (self-cancelling).

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Figure 2.2: Intrasystem EMC Loop Voltage Equations — Common "Grounds"
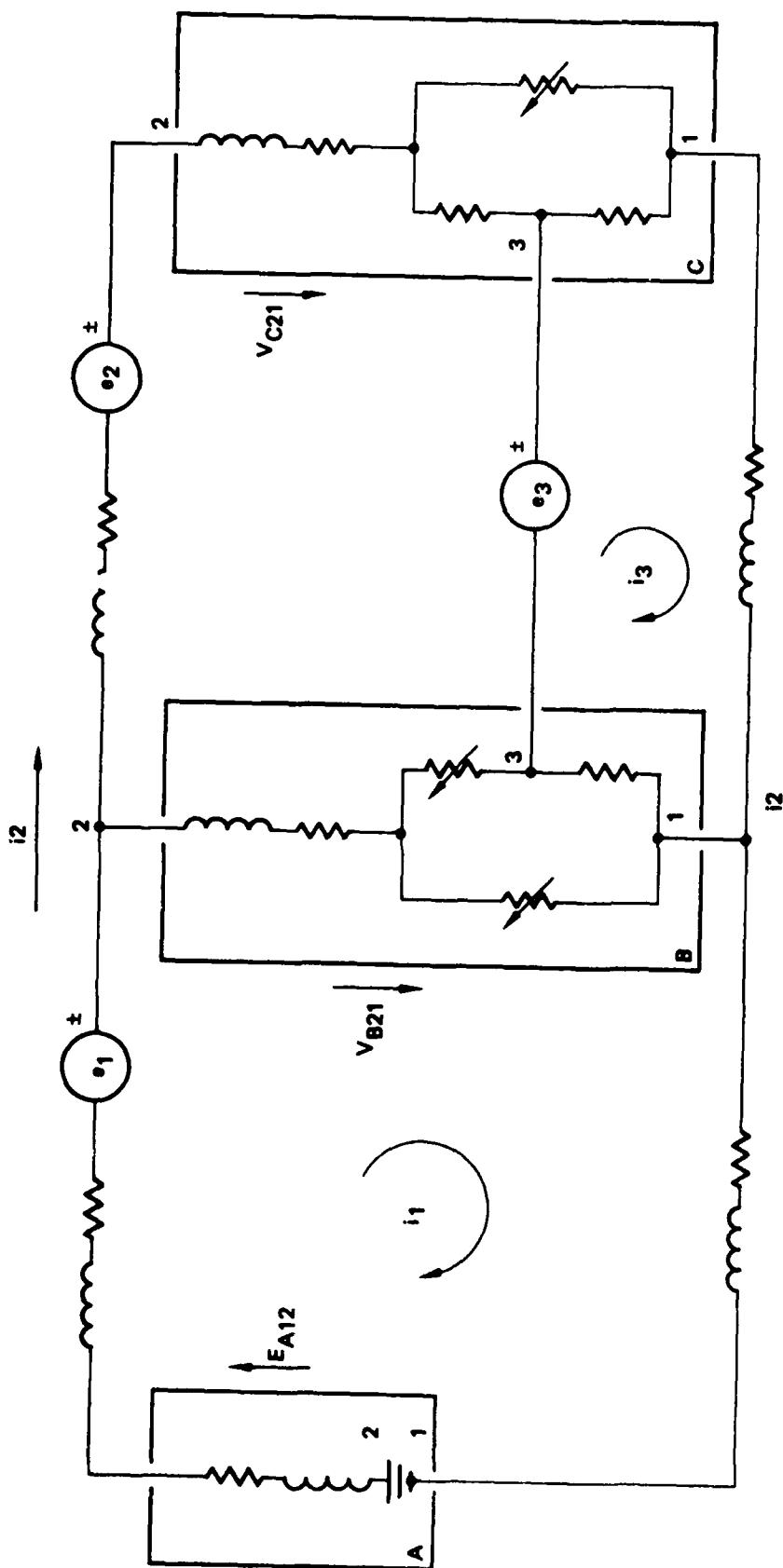
(A) IDEAL EQUATIONS (LABORATORY EQUIVALENTS)

(1) $E_{A12} - V_{B21} = 0$

(2) $E_{A12} - V_{C21} = 0$

(3) $e_{B13} - \nu_{C31} = 0$

(B) REAL EQUATIONS (SYSTEM EQUIVALENTS)

(1) $E_{A12} - V_{B21} = i_1(Z_{A2B2} + Z_{B1A1}) + i_2(Z_{A2B2} + Z_{B1A1}) + E_1$

(2) $E_{A12} - V_{C21} = i_1(Z_{A2B2} + Z_{B1A1}) + i_2(Z_{A2B2} + Z_{B2C2} + Z_{C1B1} + Z_{B1A1}) + i_3(Z_{C1B1}) \pm e_1 \pm e_2$

(3) $e_{B13} - \nu_{C31} = + i_2(Z_{C1B1}) + i_3(Z_{C1B1}) \pm e_3$

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The Z terms can never be zero as they represent line and source impedances and will always have positive values. The current terms i_2 and i_3 are functional realities and must be non-zero. Thus, the only way the iZ terms can ever be zero is if i_2 and i_3 are instantaneously equal and opposite. This will never be the case as i_2 represents the total load current for subsystem element C and i_3 is some fractional part of the subsystem element B. The voltage e_3 represents a voltage induced by nearfield and/or farfield electromagnetic coupling and can be zero only if all field values are zero. It is therefore concluded that none of the terms can be zero and compatibility must be achieved in the presence of possible interference by some compatible combination of the S:C:R relationship.

What voltage magnitudes are acceptable acknowledging that the magnitudes can never be zero? The practical answer is that <u>any level is acceptable that does not cause unacceptable performance</u> of system elements. This becomes a dilema—S limits can be imposed only if the R limits are known and vice versa. In the past EMI specifications have attempted: (a) limiting voltages, (b) limiting currents, (c) limiting susceptibility characteristics, and (d) limiting source and susceptibility characteristics and standardized impedance values, etc. In many cases these circumstances have resulted in unnecessary testing, added weight, delayed schedules, and reduced reliability without proportional EMC benefits.

Recognizing that problem voltages result from branch currents which share common impedances gave rise to the isolated loop design shown on Figure 2.3 and the single point ground concept which is a derivation thereof. (Note: The example uses an ac source but dc-dc converter technology permits the discussion herein to be equally appropriate for dc powered systems). This design eliminates the power line common impedance and is an EMC improvement. This is less than an ideal situation and still presents system design tradeoffs:

a. Power source impedance effects remain even though the common wire impedance is removed.

b. System weight and volume are increased because of the increased number of trans-formers and connectors.

c. System power requirements are increased because of the increase in the number of transformers.

d. Signal transformers are generally not compatible with high speed digital circuits.

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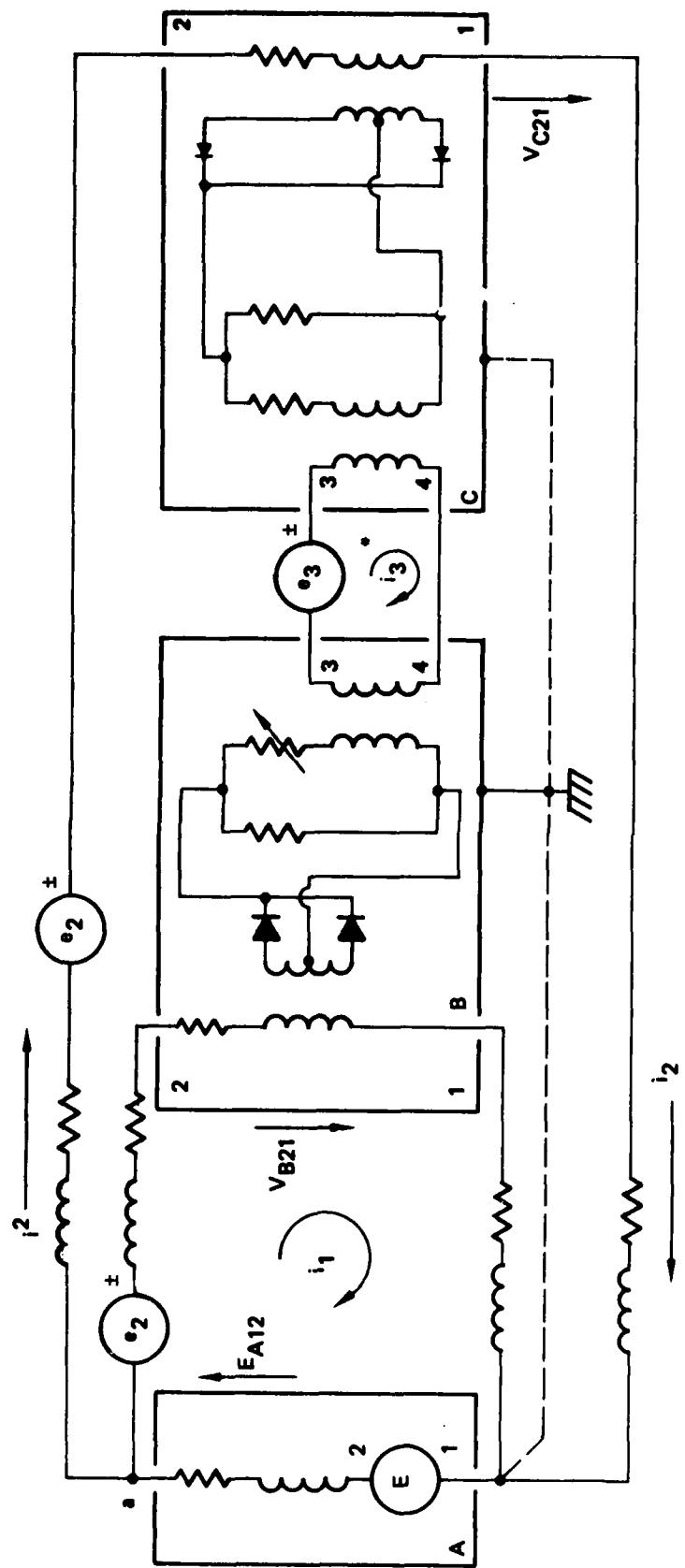
(A) IDEAL EQUATIONS (LABORATORY EQUIVALENTS)

(1) $E_{A12} - V_{B21} = 0$

(2) $E_{A12} - V_{C21} = 0$

(3) $e_{B43} - \nu_{C34} = 0$

(B) REAL EQUATIONS (SYSTEM EQUIVALENTS)

(1) $E_{A12} - V_{B21} = i_1(Z_{A2B2} + Z_{B1A1}) + i_2(Z_{A2a})$ ± e_1

(2) $E_{A12} - V_{B21} = i_1(Z_{A2a})$ $+ i_2(Z_{A2C2} + Z_{C1A1})$ ± e_2

(3) $e_{B43} - \nu_{34} =$ ± e_3

* PRESUMES SIGNAL LINE IMPEDANCE IS NEGLIGIBLE

Figure 2.3: Intrasystem EMC Loop Equations – Isolated "Grounds"

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e. Added components decrease the reliability of the system and increase system cost and logistic complexity.

There are other considerations but these are the more serious and obvious ones.

As noted previously, the voltage terms e_1, e_2, e_3 on Figures 2.2 and 2.3 represent induced voltages. Whereas the iZ drops are conducted current and conductor impedance products that occur along the wire boundaries of a topological network, the induced voltage terms result from time varying electromagnetic fields originated remotely from the wires of concern. Describing and analyzing even the simplest electromagnetic field system can be extremely difficult and usually involves wire-to-wire or field-to-wire coupling situations. The general analytical approach is to apply worst case conditions, e.g., long parallel isolated wire runs separated only by insulations. This eventually leads to the conclusion that coaxial cables are better than twisted wire pairs with shields; which are in-turn better than twisted wire pairs; which are in-turn better than isolated wires with remote returns. This line of reasoning is not incorrect but frequently overburdens a system with excessive wires, shields, and connectors; and without in depth EMC analysis unjustifiably sacrifices other system parameters for the sake of EMC conservatism.

For example, assume that N electrical interface circuits are involved. Using the dedicated transmit-return two wire concept generates a wire number requirement of 2N, i.e., a wire pair for each function. If a single common return were permissible the requirement would be N+1 wires, and if $N > 1$ wires exist, the wire number, weight, and associated connector pins are reduced by half. Whether the number of wires is 2N, N+1, or an intervening value is a decision which must be made during the system synthesis phase when interface connector pin assignments are made; this requires an effective IAP very early in the system design.

The tendency, by reason of education and/or experience for the analyst, is to think in terms of steady state, sinusoidal conditions or periodic functions that can be represented by a Fourier spectrum. For whatever reason the EMC disciplinarian adopts this approach; it is reinforced by EMI specifications such as MIL-STD-461 where the preponderance of testing is directed towards tuned receiver measurements. This approach tends to obscure the fact that transients cause many intrasystem EMC problems. Integrated Electrical systems are not always properly tested for transients; and, if the

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transients happen to be of a probabilistic or random nature, may go undetected. Equipment level EMI specifications have attempted to characterize the transient susceptibility problem by imposing power line susceptibility injection tests, "chattering relay" tests on cables, etc. Such tests are usually ineffective, particularly in relationship to present digital technology. For example, the power line worst case transient test specified by MIL-STD-461 is 0 to 100 volts in 2.5 microseconds, a rate of 40 million volts per second. On the other hand a digital circuit which can switch 0 to 5 volts in 5 nanoseconds has a rate of 1 billion volts per second. This means that logic signal lines will produce cross wire coupling that is 25 to 100 times greater than the MIL-STD-461 susceptibility test resulting in an undertest of 28 to 40db for some cases. The digital device switching speed is the reason distributed capacitance is required at the device power terminals, i.e., distributed electrical energy sources are required to compensate for the distributed line inductance between the power source and digital load as electrical energy cannot be instantaneously transformed nor transported.

As added emphasis to possible digital circuit problems, one semiconductor manufacturer has recently disclosed laboratory devices capable of controlled switching speeds in the 40 picosecond range. Assuming a linear transition and a "times 4" stability factor, this switching speed is approximately equivalent to a 6 GHz signal which is in the radar frequency range. Typically, a number of cycles are integrated to develop a data factor for radar (intermediate frequency dependent), these digital logic components (soon to be available) will develop their data factor in 40 picoseconds. If EMC tests are presently considered inadequate for digital circuits, they will be even more inadequate (20 to 30 dB) when these faster components become available. Qualitative transmission line theory can be used to illustrate the nature of transient problems associated with high speed digital circuit signal lines.

Figure 2.4 illustrates linear ramp voltage and current waves initiated by some source to the left of the transmission line. The waves travel to the termination and will be absorbed or partially reflected. When a reflection occurs one wave will spatially reinforce the original source wave and the other will oppose the original source wave. If the enhancement is associated with the voltage wave, then capacitive coupling is enhanced and inductive coupling diminishes. If the enhancement is associated with the current wave, then inductive coupling is enhanced and capacitive coupling decreases. Step function transmission line techniques can be used to illustrate several aspects of transient wave fronts in a system. Table 2.1 has been prepared for the case where a step

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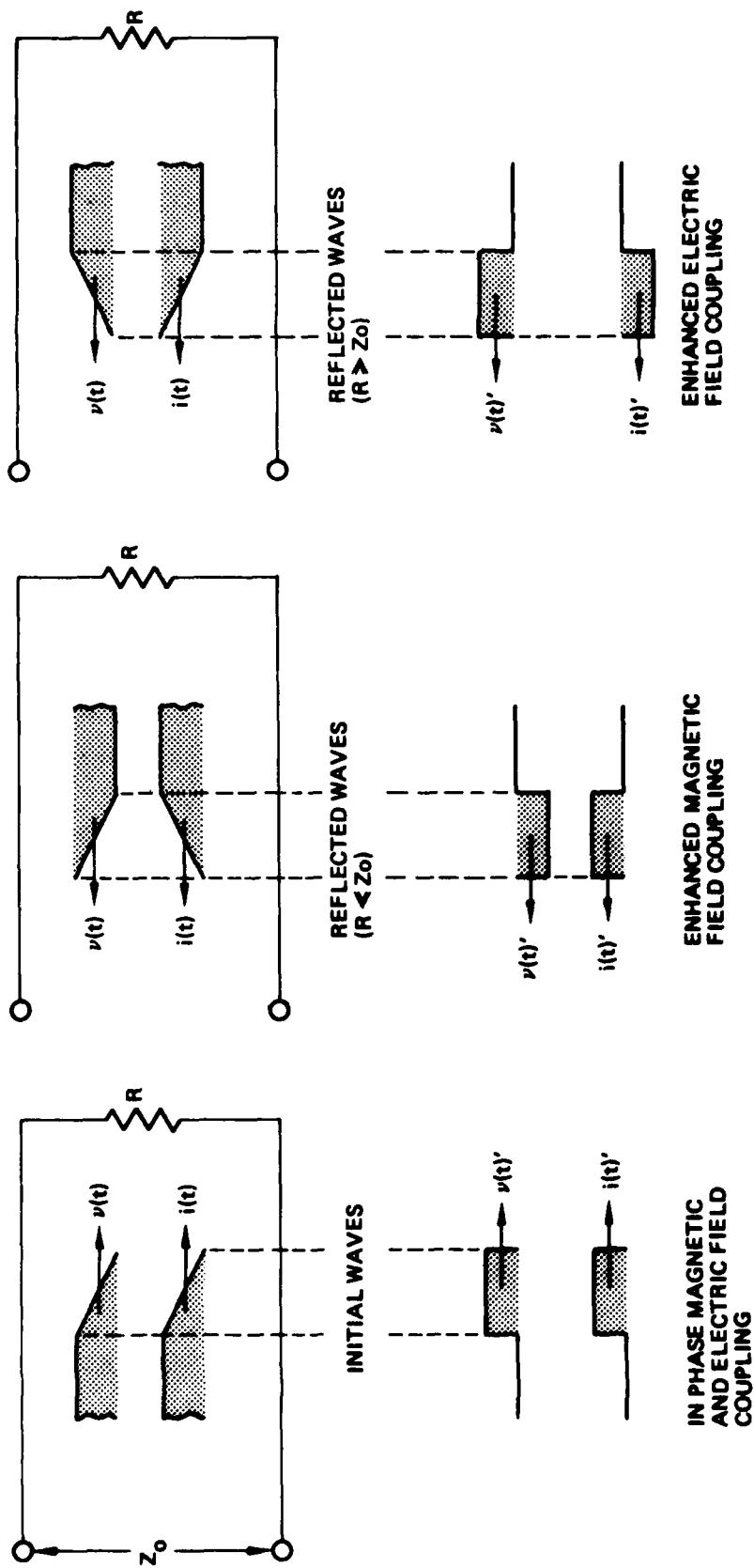
Figure 2.4: Initial Wave and Reflected Wave Coupling Relationships

R

v(t)   i(t)

REFLECTED WAVES
(R > Zo)

v(t)'   i(t)'

ENHANCED ELECTRIC
FIELD COUPLING

R

v(t)   i(t)

REFLECTED WAVES
(R < Zo)

v(t)'   i(t)'

ENHANCED MAGNETIC
FIELD COUPLING

R

v(t)   i(t)

INITIAL WAVES

v(t)'   i(t)'

IN PHASE MAGNETIC
AND ELECTRIC FIELD
COUPLING

Zo

14

Table 2.1: Voltage and Current Wave Phase Relationships for Source-Line-Load Impedance Combinations

UPPER ARROW = VOLTAGE WAVE
LOWER ARROW = CURRENT WAVE

REFERENCE NUMBER	SOURCE VOLTAGE REFLECTION COEFFICIENT	SOURCE CURRENT REFLECTION COEFFICIENT	SOURCE-LINE-LOAD IMPEDANCE RELATIONSHIPS	LOAD VOLTAGE REFLECTION COEFFICIENT	LOAD CURRENT REFLECTION COEFFICIENT	WAVE NUMBER: 1	2	3	4	5	6	7	8
1	0	0	$Z_s = Z_o = Z_L$	0	0	←←							
2	+	−	$Z_s > Z_o = Z_L$	+	0	←←							
3	−	+	$Z_s < Z_o = Z_L$	−	0	←←							
4	0	0	$Z_s = Z_o < Z_L$	+	−	←←	←→						
5	0	0	$Z_s = Z_o > Z_L$	−	+	←←	→←						
6	−	+	$Z_s < Z_o < Z_L$	+	−	←←	←→	→→	→←	←←	←→	→→	→←
7	+	−	$Z_s > Z_o > Z_L$	−	+	←←	→→	→→	←→	←←	→←	→→	←→
8	+	−	$Z_s > Z_o < Z_L$	+	−	←←	←→	←←	←→	←←	←→	←←	←→
9	−	+	$Z_s < Z_o > Z_L$	−	+	←←	→←	←←	→←	←←	→←	←←	→←

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function source voltage is applied to a transmission line network for different source and load resistance relationships to illustrate the 9 possible wave and coupling conditions.

a. For the first 3 cases where only the line and load are matched the system will experience single voltage and current wave fronts.

b. If only the source and line are matched as for cases 4 and 5, there will be two wave fronts as shown in Figure 2.4 in which either the voltage or current wave is enhanced and the other is diminished for the reflected wave.

c. Cases 6 and 7 of the table present an oscillatory condition for both waves with a period that is 4 times the electrical line length.

d. Cases 8 and 9 present enhanced E or H field wave fronts with the other wave oscillating at a period of 2 times the electrical line length.

Since most transmission lines permit wave velocities in the range of 1/3 to 2/3's of free space velocity, the narrowest pulses coupled to the line can be expected to be on the order of 2 to 4 nanoseconds for each foot of line separating interface nodes. If this line of reasoning is pursued, two conclusions are apparent: (1) Electrical transient conditions often go undetected in digital circuits; and (2) the nature of testing for electrical transients is to analytically presume the transient exists and test accordingly. These conditions imply instrumentation methods of "single shot" measuring capability and negate the continuous sine wave methods. If instrumentation is not available to meet these requirements then mirror circuit imaging or "mouse trap" measurement techniques may be necessary. (Note: A mouse trap is considered to be a function detector which detects a condition and latches or freezes all subsequent events.)

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Up to this point the discussion has been directed at the S and C aspect of the EMC problem with only references to IC component susceptibility. Digital and analog IC susceptibilities will now be discussed in terms of their R relationship.

Line-to-line coupled pulses are of great concern for digital circuits when memory interface circuits are involved. A single pulse, such as that presented by Figure 2.4 and Table 2.1, can cause a false data condition or it can cause a transmission to be aborted (if message check schemes are used to check for bad data bits). Determining whether an interfering condition exists for line-to-line coupling is not easy as it involves line lengths, terminating impedances, response times, and timing of the affected component or circuit. Nonmemory digital interface circuits may also be affected by single pulses but not likely to cause system problems unless the transient rise time (fall-time) exceeds the data or clock period.

Analog as well as digital ICs have been shown to be susceptible to frequencies several magnitudes above their normal mode band pass. One government sponsored test project provides extensive component data in terms of threshold sensitivity and also provides some data on IC performance degradation and catastrophic failure (1). The data was acquired using special designed test fixtures for direct rf injection to the IC which minimized test set-up variables. Thus, the data is probably as near "pure" component susceptibility characterization data as can be reasonably acquired. Devices which were tested included generic and functional component families as follows;

a.   TTL: 7400, 7402, 7404, 7405, 7408, 7432, 7450, 7473 and 7479;
b.   CMOS: 4011A, B, 4007A, B, 4001A and 4013A;
c.   Line Driver-Receivers: 8830-8820, 9614-9615, 55109-55107A and 55110;
d.   Operation Amplifiers: 741, 108A, 201A, 207, 0042C and 531;
e.   Voltage Regulators: 309, 320, 70MO5, 300 and 305, and;
f.   Comparators: 306, 311, 339, 360, 710 and 760.

Tests were conducted at frequencies between 0.1 and 10 GHz with presumably sufficient numbers of each type to statistically characterize each component. Thresholds were determined for signal input and other input terminals with threshold levels varying for the leads of each component and/or family. Figure 2.5 is a composite plot of worst case thresholds at the onset of rf effects with hard failures occuring (in most cases) 10 to
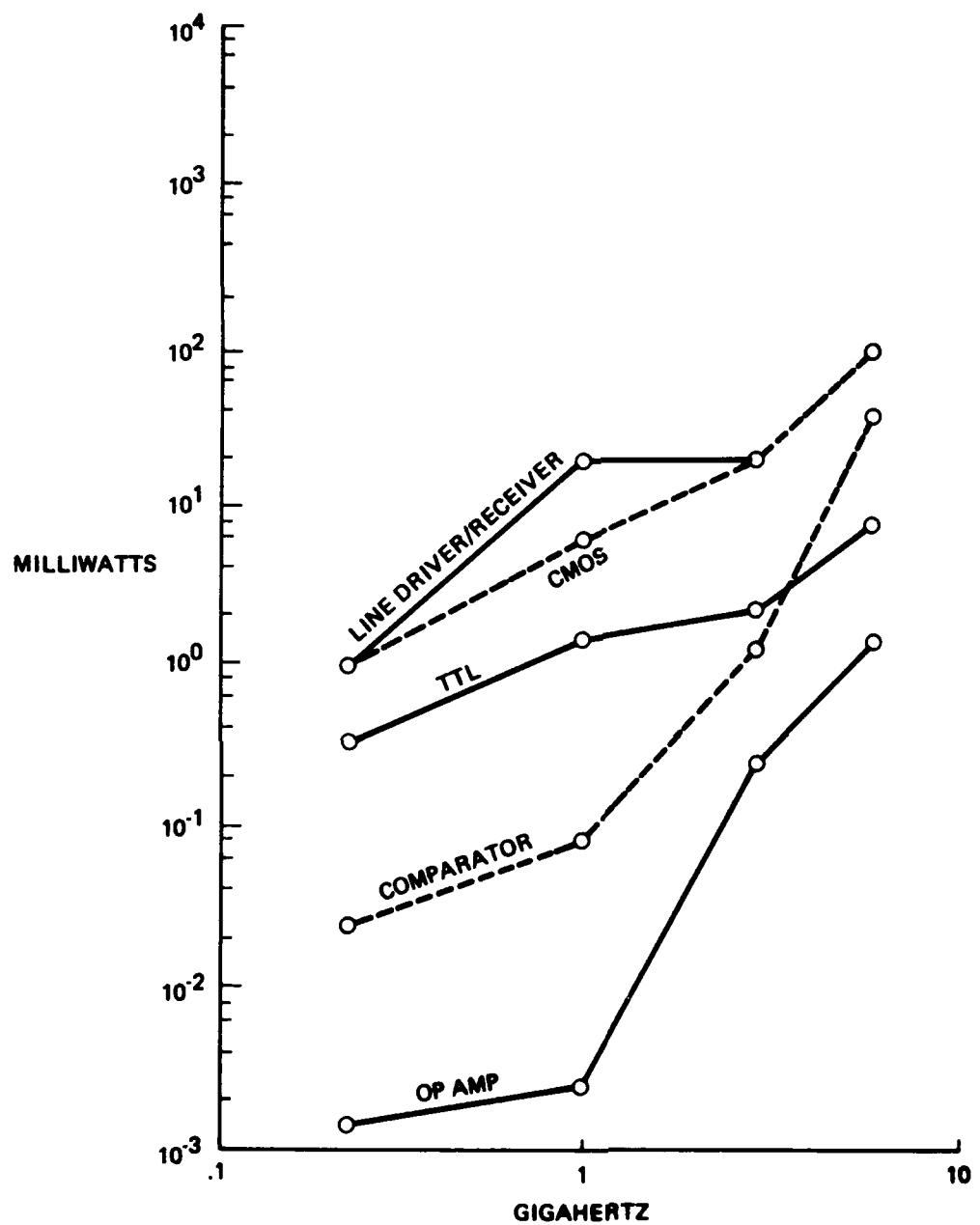
Figure 2.5: Relative RF Susceptibility Thresholds of Integrated Circuits
as Reported by DTIC Report AD A059 442

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20 dB above the values noted. The susceptibility mechanism apparently involves the nonlinear detection capability of component diode junctions and associated junction capacitances. The report also uses the code ISPICE (Interactive Simulation Program with Integrated Circuit Emphasis) and Ebers-Moll model to correlate computed and empirical data, however, R. E. Richardson has extended the rf effects to causes beyond the previously mentioned model's accountability [2]. Irrespective of the theoretical and laboratory aspects of IC rf susceptibility, the situation is real as evidenced by many field problems whereby interface wires to IC's serve as antennae and the IC does respond as an rf detector. These theoretical and empirical results regarding IC rf susceptibility data are directed at the smallest isolated element possible and do not account for other circuit elements. This may cause some conceptual confusion in applying the S:C:R relationship, i.e., S could be represented by far field radiation or a wire generated electromagnetic field, C is represented by the interface wire to an IC which constitutes an antenna, and R is represented by the IC. Would an inline filter be characterized as a part of C or a part of R? This appears to be a trivial point but one that has to be considered when creating analysis models and developing computation codes.

The preceding discussion obviously applies to other than IC circuits, but they have been singled out for two reasons - 1) all design trends are towards greater usage, and 2) each generation of semiconductor elements tends to be a lower power device. Both conditions indicate a greater probability of EMC problems. As the electronic packaging density increases it becomes less possible to probe and test at the level desired without introducing EMI effects. A resulting conclusion is that EMC tests will have to be more sophisticated and less "brute force" in manner.

2.1.2 Intersystem EMC Overview

An intersystem condition as used herein is not the electrical union of two or more systems illustrated by Figures 2.2 and 2.3; in this report a system interface boundary is presumed when intentional copper connections cease. The intersystem concept intended is that system elements do not require the interfaces to be functional, but the interfaces must be limited or controlled for the system to remain functional. Controlled interfaces may be of many forms, but major concerns for all systems are lightning, electromagnetic radiation (EMR), and nuclear electromagnetic pulse (NEMP). Charging effects are also a major concern for airborne and spacecraft systems.

Since intersystem EMC characteristics are seldom tested, even on a small scale basis, compatibility relies principally on analysis. An obvious exception to this is field testing of EMR conditions either planned or unplanned. Seldom does a contractor have the facilities to simulate field conditions. Thus, from the contractual and administrative viewpoint, EMR, NEMP, and lightning system survivability and operability rely on design analysis. This is contrary to the intrasystem EMC situation where achieving compatibility has three opportunities - design, developmental testing, and/or performance testing.

2.2 MIL-E-6051D, Systems Electromagnetic Compatibility Requirements

This is an absolutely unique document in that quantized values appear in only four places (3.2.3.1, 3.2.7, 3.2.8.1.1 and 3.10.2)*. Yet it is undoubtedly the most reasonable of all government EMI/EMC specifications and contains three fundamental requirements—

a. All equipment must perform their intended functions without unacceptable interference effects (3.2.1);

b. A complete compatibility test must be performed (4.3.1) with the procurement agency and contractor (PAC) mutually deriving and developing the means to these ends (3.2.3, 3.3, 4.2, 4.3); and,

c. Each production system shall be given a limited acceptance test to ensure production compliance is maintained (4.3.2).

The general requirement specifies that EMC is to be designed into the system and not occur after-the-fact; and it also lists some general design topics (3.2). Three areas which mandate early EMC analysis efforts are minimal use of filters, external environment considerations, and use of existing system test points rather than special test, breakout boxes (3.2.14, 3.2.13, and 3.2.3.1, respectively).

Specification compliance is achieved when compatible operation (including approved safety margins) is demonstrated without unacceptable responses or malfunctions (4.5.1). Degradation criteria for each subsystem/equipment shall be derived by the PAC,

*Numbers in parenthesis correspond to specification subsections.

and those assigned criticallity I or II categories will exhibit a safety margin beyond the existing level of potential interference. The safety margins are variable, but unless otherwise specified shall not be less than 6 dB for nonordnance circuits or 20 dB for ordnance circuits (3.2.1, 3.2.3 and 3.2.3.1). Safety margins presume that all equipment has achieved functional compatibility and the PAC has mutually derived any safety margin criteria.

A most ignored aspect of MIL-E-6051 lies in subsection 3.2.4.1 as follows:

"**3.2.4.1 Subsystems/Equipments.** Unless otherwise specified in the contract, subsystems/equipments shall be designed to meet the requirements of MIL-STD-461 and MIL-STD-462. Since some of the limits in these standards are very severe, the impact of these limits on system effectiveness, cost and weight shall be considered. Proposed modifications to the limits shall be included in the system EMC plans for the system and subsystems/equipments. In addition, for Air Force procurements, AFSC manual 80-9 (volume IV), Electromagnetic Compatibility shall be used for general design guidance and criteria."

This statement does not require or force compliance with MIL-STD-461 test provisions. However, it specifically recognizes the impact that blind adherence to MIL-STD-461 can have on a system. Partial or complete forfeiture to MIL-STD-461 is a matter of choice by program administrators be they government or contractor. MIL-E-6051, originally released in July 1967, proposed limit tailoring; MIL-STD-461 Rev B, released in May 1980, finally adopted tailoring of specification limits.

A system compatibility test on the first article system which verifies EMC margins, and, retests due to significant configuration changes are required (4.3.1). In addition a general acceptance test provision requires a limited test be performed on each system produced (4.3.2). The latter test should always include real time, recorded measurements of power bus(es) for all critical mission events.

MIL-E-6051D is not without some inconsistencies. (a) It is unreasonable to expect that each wire or cable be specifically and visually identified for its "EMC category" (3.2.5). If the EMC designer is involved in the initial layout and design of

subsystem interfaces, wire and cable locations should be established and known; if a character or color code can be added to an existing coding scheme of wire and cables, then the EMC categorization is reasonable; otherwise it is difficult to justify. (b) Permitting 50 microsecond, +50%, -150% amplitude transients on aircraft dc power buses contradicts the specifications principal·objective, i.e., the system must operate irrespective of individual hardware characteristics (3.2.7). Absolute values are irrelavent at the system level as EMC margins are based on relative values and invoking absolute values encourages inefficiency (Note: Standards are primarily used to attain uniformity and specifications uniqueness. In this context a specification is used to achieve an acceptable system and a standard to maintain the quality of subsequent systems). (c) The requirement for conductive backshells and peripheral shield bonding is extremely desirable but should be "mission justified" as it is expensive and burdens the system (3.25).

2.3 MIL-STD-461, EM EMISSION SUSCEPTIBILITY REQUIREMENTS FOR THE CONTROL OF EMI

There are two versions of MIL-STD-461, MIL-STD-461A and MIL-STD-461B. Since version B is intended to eventually be the sole version, only it will be addressed in this report except for IEMCAP discussions because it's code is based technically on the A version.

There are 10 parts of the specification with the first part being general requirements. A particularly important aspect is the provision for tailoring (Part 1, 3.8). Theoretically, any requirement may be modified to be more or less stringent for an equipment or subsystem without processing a waiver or deviation. The act of tailoring is predicated on engineering analyses and implemented by the procuring activity as necessary to achieve integrated system performance with regards to electromagnetic compatibility (EMC), electromagnetic interference (EMI), electromagnetic pulse (EMP), electromagnetic radiation (EMR), etc. controls (Part 1, 1.2). These requirements are explicit in version B, whereas they were implicit, nebulous, or nonexistent in version A. The tailoring capability presents an excellent opportunity to control design and testing but will require a credible IAP and cooperative procuring agency and contractor.

Another significant and new requirement of version B is to perform suscepti-bility tests to the Unit Under Test (UUT) failure threshold or to the test equipment's limitation, (Part 1, 4.9). This is an attempt to characterize the UUT's actual performance limits in the presence of EMI and typifies the trend in EMI testing. Table 2.2 has been constructed to illustrate the differences between MIL-STD-461A and MIL-STD-461B. Whereas MIL-STD-461B shows a 40% reduction of emission tests from MIL-STD-461A, there is only an 8% reduction in susceptibility tests. This stricter emphasis on susceptibility thresholds is largely because many, if not most, EMI problems result from non-linear and stray coupling or resonant conditions which are unaccounted for in general linear analyses.

A single test which combines several untested equipments into an actual or pseudo subsystem is advised in the interest of test effectiveness and efficiency (Part 1,4.9). This was also a provision of the "A" version of the standard but seldom implemented because of contracting problems it presents between prime contractor and subcontractor. For example compliance with the absolute values of MIL-STD-461 by the subcontractor is a means of closing out contracted obligations but if the prime contractor

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Table 2.2: *MIL-STD-461B Part Effectivities and MIL-STD-461A/MIL-STD-461 B Comparison*

	TEST CATEGORY			
	CONDUCTED EMISSIONS 1 2 3 4 5 6 7	CONDUCTED SUSCEPTIBILITY 1 2 3 4 5 6 7 8 9	RADIATED EMISSIONS 1 2 3 4 5 6	RADIATED SUSCEPTIBILITY 1 2 3 4
MIL-STD-461 A				
MIL-STD-461 B				
PART 2				
3				
4				
5				
6				
7				
8				
9				
10				

PART 2 AIRCRAFT & GSE EQUIPMENT
       3 SPACE VEHICLES & GSE
       4 GROUND FACILITIES
       5 SURFACE SHIPS
       6 SUBMARINES

PART 7 PHYSICALLY REMOTE EQUIPMENTS IN SUPPORT OF 2 THROUGH 6
       8 TACTICAL & ENGINE DRIVEN EQUIPMENT
       9 MOBILE POWER GENERATION EQUIPMENT
    10 COMMERCIAL NON-ELECTRONIC HARDWARE

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performs the test how does the subcontractor meet his obligations to provide EMC acceptable hardware. This situation along with the undefined susceptibility limit will, in some manner, have to be managed as a part of tailoring.

A possibly detracting provision of version B is requiring "short duration emissions" to meet the requirements of the standard (Part 1, 4.7). A new test (CE07), in an attempt to be consistent with MIL-E-6051 and MIL-STD-704, has been added which permits AC power lead transients of $\pm$50% and DC power lead transients of +50%, -150%, (Part 2, 5.2). Although MIL-STD-462 has not been revised to include a procedure for the test, it is a poor requirement since it conflicts with the tailoring concept. The genesis of this requirement is believed to be based on aircraft employing switch over between prime power sources of an inductive nature. This requirement should have remained a MIL-STD-704 requirement and should be written into tailored, MIL-STD-461B requirements only when deemed necessary.

The foregoing discussions mainly concerned Part 1 of MIL-STD-461B, but as noted on Table 2.2 there are 9 additional parts to the specification. These 9 parts are an attempt at "pretailoring" presumably based on the particular needs, experience or mission of the different military services. Within a particular part, additional pretailoring is attempted by equipment classifications or test limit variations. For example, CS06 peak amplitude and pulse width limits are as follows:

> Part 2, 200 volts and 10 microseconds (Army), 200 volts and 150 nanoseconds (Air Force and Navy);
> Part 3, 200 volts and 10 microseconds, 100 volts and 150 nanoseconds (sic);
> Part 4, 100 volts and 10 microseconds (Army), 400 volts and less than 5 microseconds (Air Force and Navy);
> Parts 5, 6 and 7, 400 volts and 5 microseconds.

Technical differences illustrated by this CS 06 example exist throughout Parts 2 through 10 and the specification itself should be referenced for details and particulars. However the general scope and character for each test can be established by examining the CE, CS, RE and RS test requirements for Part 2 since it requires all test categories contained in MIL-STD-461B. This examination is presented in the following subsections commencing with the conducted emission test CE 01.

CE 01

This test requires a narrowband, current probe measurement of power leads and power returns which are not chassis terminated; other leads may be tested with the testing justified through tailoring. Test limits are 130 dBuA from 30 Hz to 2 KHz then decreasing logarithmically linear (log lin) to 86 dBuA at 15 KHz. The test is required only for equipment installed on airplanes with antisubmarine warfare capability.

This provides spectral data for AC powered equipment and for fixed frequency, DC converter powered equipment. The increase in the limit from 120 dBuA (in version A) to 130 dBuA (in version B) is an attempt towards physical reality as a 1 ampere limit for 60 and 400 Hz powered equipment was too restrictive. However, the 2 KHz breakpoint maybe too low to accommodate dc-dc converters. Since DC systems are typically +24 to +28 vdc power, for a given functional load, they require a limit which is 12 dB greater than it is for 115 VAC systems; filtering or tailoring may therefore be mandatory.

The requirement exists to measure both power lines and ungrounded power returns but only the power line when chassis/structure is used as a return. The former is a preferred design approach and presents the lesser probability of EMC problems yet it requires more testing. This is a test penalty on the better designed system and should be appropriately dealt with in the EMC tailoring or control plan.

CE 03

This test is an extension of CE 01 and it includes broadband as well as narrowband measurements. Narrowband limits are 85 dBuA at 15 KHz decreasing log lin to 20 dBuA at 2 MHz and then are constant to 50 MHz; broadband limits are 130 dBuA/MHz at 15 MHz decreasing log lin to 50 dBuA/MHz at 2 MHz and are flat to 50 MHz. This test is particularly severe on DC-DC converters since the power transistor switching capability can be greater than 50 KHz and the limit is in the 10 to 100 milliampere level in this frequency range. An effective IAP is desireable to avoid unnecessary filtering and tailoring of DC converters.

The upper frequency limit of 50 MHz is probably too high for power line conducted tests of this type. In addition to the data being dependent on the power source and UUT, test set-up (distributed and lumped) parameters will affect the measurements

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and this will more than likely result in one or more resonances that are unrepresentative of the UUT.

CE 06

This test requires measurement of voltages at the antenna terminals of receivers and transmitters. Narrowband voltage limits are 34 dBuV and broadband voltage limits are 40 dBuV/MHz excluding the transmitters necessary bandwidth or $\pm 5\%$ of the fundamental frequency. Transmitter key down harmonics and spurious emissions, excluding the second and third harmonics, are required to be less than -80 dB of the fundamental peak power, and the second and third harmonics are required to be less than -40 dB minus 10 log (peak power) (watts) or 80 dB, whichever "requires less suppression." MIL-STD-462 presents 3 test configurations with a deferral to REO3 if the transmitter power is greater than 37 dBW or the operating frequency is greater than 1.24 GHz. Other MIL-STD-462 stipulations are:

a. The procedures do not apply to equipment designed to operate into a fixed non-removable antenna.
b. Three separate test set-ups are specified depending on the available terminal power; in the case of CE06-3 the UUT antenna is placed in an anechoic chamber.

The objective of this test is to obtain RF spectral data available at open terminals, leaky connections, and/or antenna ports.

CE 07

This test requirement specifies that AC powerline transient limits be set at $\pm 50\%$ nominal rms and that DC limits be set at +50% and -150% nominal VDC. This test does not have a duration limit and is applicable to sources and loads. This is a new MIL-STD-461 requirement carried over from MIL-E-6051 where the transient duration is 50 microseconds or less; a test procedure has not been added to MIL-STD-462.

This test requirement is a step in the proper direction regarding powerline transients. However, the amplitude limits are severe for a general requirement and may

be in error for omitting a duration limit. System powerline transients are a function of the load, power source, and distribution network (reference Section 2.1.1). Decreasing voltage conditions are generally indicative of increased loading, and overvoltage conditions are indicative of decreased loading. The -150% dc voltage requirement is an attempt to account for step function inductive unloading; a system designed for EMC will not permit -150% voltage excursions and the actual limit should be based on system requirements and determined through tailoring.

CS 01

This series of tests modulates input power leads/ungrounded power returns at voltage levels the lesser of 5V rms or 10% supply voltage from 30 Hz to 2 KHz log lin decreasing to the greater of 1V rms or 1% supply voltage at 50 KHz. Should the UUT fail during the test, the interference level is reduced until normal operation returns; this is the UUT threshold level. However, susceptibility testing is now required to test beyond the limit to a failure threshold or instrumentation limits (Part 1, 4.9).

MIL-STD-462 test limitations presently exclude the test when frequencies are within 5% of power frequencies and when the test apparatus can deliver 50 watts to a 1/2 ohm load but still not provide the interference test value.

This test is an attempt to simulate voltages induced in a power loop due to nearby power circuits and is not representative of the transient conditions discussed in 2.1 and implemented by the new CE 07 test. An expanded discussion will be presented in Section 3 on this matter.

CS 02

CS 01 covers the audio frequency range, this test causes the input power terminal and the ungrounded power return terminals to be subjected to an rf level of up to 1V rms over a swept frequency range from 50 KHz to 400 MHz. Since the injected signal is applied through a series capacitor and is in parallel to the UUT power terminal and its power source, injected current levels into the UUT are never determined. If a failure should occur, the threshold value is relative to the manner of test and the characteristics of the capacitor, power source, and coupling path from the UUT terminals to the power source.

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This test is similar to RS testing except RS testing exposes the UUT's wiring to common mode pickup whereas this is a differential mode exposure by direct injection.

CS 03

This is an intermodulation test for amplifiers/receivers which operate between 30 Hz to 10 GHz and the test requires two signal generators. The frequency test range covers 0.1 to 10 times the UUT's fundamental frequency with a modulated signal reference level of 66 dB above nominal signal input level but detuned to a frequency that provides zero UUT output. The second signal is frequency swept at an unmodulated level of 66 dB above the level which causes a nominal in-band output. When intermodulation effects occur both generator outputs are reduced equally to the point of nominal UUT output to establish the intermodulation rejection level. The test procedure is repeated for two particular frequency bands, 2 to 25 MHz and 200 to 400 MHz, but is repeated at 80 dB above nominal input level.

This test simulates a through the antenna interference condition representing a CW signal in the presence of a normal modulated signal. The criteria for success is that no intermodulation products exist beyond UUT allowables. This establishes a front end UUT frequency-amplitude rejection characteristic.

CS 04

This is a signal to noise test, for receivers and amplifiers which operate in the 30 Hz to 10 GHz range requiring two signal generators with one modulated signal set for nominal operation and the second generator simulating a CW interference signal 80 dB above the modulated signal. Frequency test range is $.05f_1$ to f_1 and f_2 to $20f_2$ where f_1 and f_2 represent -80dB values below and above the UUT's center frequency, respectively. The receivers' frequency test range may be expanded at the lower end if 1/5 the IF frequency is less than f_1, and at the upper end if the sum of 5 times the local oscillator frequency and the intermediate frequency is greater than f_2.

The comments made for CS 03 are also appropriate here.

CS 05

This is a test of receivers and amplifiers that is used to determine cross modulation products for a fixed CW signal input while the interfering signal is modulated and swept across the fundamental $\pm$ intermediate frequency range. The interfering signal level is 66dB above the reference level as determined for CS 03.

As with CS 03 and CS 04 this test establishes unacceptable performance and interfering thresholds which can be used for antenna coupling situations.

CS 06

This test causes a repetitive 200 volt, 150 nanosecond pulse to be injected across the UUT's input power leads with the criteria for success being no unacceptable UUT response. Polarity reversal tests are performed as well as sychronized pulse tests for AC power systems and master clocked digital equipment. If unacceptable responses occur, threshold levels are obtained.

This test attempts to ensure some protection from network transients associated with de-energized inductance and step function switching. However, the Air Force/Navy pulse width requirement of 150 nanoseconds and the Army's corresponding 10 microsecond duration are not compatible. This issue will be addressed further in Section 3.0 in conjunction with the new CE 07 test.

CS 07

This test determines the effects of an impulsive signal on the squelch circuit of receivers for two cases. For the first case the impulse level is 90 dBuV/MHz directly into the receiver. In the second case the impulse level is 50 dBuV/MHz simultaneously applied with an unmodulated CW at the fundamental frequency and 2/3's the amplitude to cause the squelch circuit to open. The criterion for success is for squelch operation to remain for both cases.

This test, applied through the receiver input, is apparently an attempt to simulate broadband and "precipitation static" effects on audible communication circuits. It is an extension of the CS 03, 04, and 05 CW and modulated CW tests but is of

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questionable merit since it does not take into account filtering effects of an antenna on impulsive interference.

CS 09

This is a Navy test not applicable to AF systems and is not contained in MIL-STD-462. The test involves a current injection from 60 Hz at 1 ampere to 100 KHz at 1 milliampere with log lin breakpoints at 300 Hz and 20 KHz. Being applicable only to equipment with signal circuit sensitivities of less than 1 uV, leads to the assumption that it is intended to induce ground plane effects in rf receivers.

RE 01

This test results in the measurement of the magnetic field over the 30 Hz to 30 KHz frequency range at a distance which is 7 cm from the UUT and its cables. The specified limit is 140 dBpT at 30 Hz decreasing log lin to 20 dBpT at 30 KHz and remaining flat to 50 KHz.

Test effectivity is limited to airplanes with ASW capability, presumably to minimize magnetic field intensities which could affect magnetic sensors.

RE 02

This is a radiation test of the UUT and the associated cabling but the test excludes narrowband antenna radiation measurements from 14 KHz to 10 GHz and broadband measurements from 14 KHz to 1 GHz. Narrowband limits are 45 dBuV/m at 14 KHz decreasing log lin to 20 dBuV/m at 18 MHz and increasing log lin to 70 dBuV/m at 10 GHz. Broadband limits are 110 dBuV/m/MHz at 14 KHz decreasing log lin to 65 units dBuV/m/MHz at 200 MHz to 80 dBuV/m/MHz at 1 GHz.

Measurements are made at a distance of 1 meter from the test set-up and are typically made within a shielded enclosure. Loads and interface cables are simulated, and dummy rf transmitter loads are driven by shielded cable. The measurements are generally in the near field and are subject to reflections from interior test chamber walls which cause sharp peaks and nulls from standing waves. Cable lengths, ground plane dimensions, etc. can bias the data as will load simulators. Test criterion is not to exceed the

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specification limit, but typically, most equipment fails to meet the requirement and waivers/deviations are then processed. Antennas are replaced by dummy loads as any emmitted radiation would not be representative of system antenna patterns and would aggravate an already "boxed in" environment. Vertical and horizontal polarization measurements are made above 30 MHz and to attain orthogonal measurements for the test set-up but are not generally translatable to other configurations because of the test configuration effects.

RE 03

This test is an extension of CE 06 with transmitters of less than -10 dBW exempt. Limits are not applicable within ±5% of the fundamental frequency. All harmonics except the second and third must be less than 80 dB below the fundamental and the second and third less than 40 dB +10 log peak power or 80 dB whichever requires less suppression. Whereas CE 06 is to be used when possible, RE 03 will always be used if the power output is greater than 5 KW (average), the fundamental frequency is greater than 1.24 GHz, or the UUT's antenna is integral and not replaceable by a dummy load. The range of the frequency test is 10 KHz to 40 GHz and with the specific test range depending on actual operating frequencies with seven separate test bands specified in MIL-STD-462. Provisions are made for testing above 1 GHz to place measuring antennae somewhat located by far field transmission formulae but no control of multipaths. When a dummy load is used, the measurements obtained are for cable, wiring, and case emissions.

RS 01

This test is intended only for airplanes with ASW capability. It is a test for a magnetic field susceptibility and covers the 30 Hz to 50 KHz frequency range. Specification test limits are 160 dBpT at 30 Hz decreasing log lin to 115 dBpT at 500 Hz decreasing log lin to 78 dBpT at 30 KHz and flat to 50 KHz. MIL-STD-462 instructions state that current levels are to provide field strength values which are 20 to 30 dB above the test limit while probing the UUT case and cabling for maximum susceptibility indications. If an undesirable response occurs the amplitude is reduced to the response threshold.

Whereas compliance with the test limit is required, design changes based on magnetic field probing with a 12 cm loop should be thoroughly analyzed for practicality

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before commitment, i.e. the reasonableness of the test with practical coupling situations should be thoroughly analyzed as the coupling to the 12 cm loop is more severe than will be encountered in a well designed system. The 12 cm is more representative of loop areas that occur within power panels, etc., where terminal boards, buses, circuit breakers, etc. force loop areas to be inherent in the design.

RS 02

This is a magnetic field coupling test. In separate tests, insulated wire is wrapped around signal cables and around the UUT case. For each configuration the insulated wire is driven by 20 amperes at the UUT's power frequency as appropriate and by the pulse for CS 06. Threshold levels are determined for degradation conditions.

As with all other susceptibility tests, design changes to accommodate compliance must be approached with caution; test conditions are generally nonexemplary of the true system electromagnetic environment conditions where wire routing is controlled (or should be).

RS 03

This test causes the simulator and UUT cabling to be exposed to near field radiation and multipath from 14 KHz to 10 GHz. The upper frequency limit may be 40 GHz depending on specific equipment. Test limits are 10 V/m from 14 KHz to 30 MHz, 5 V/m from 30 MHz to 10 GHz, and 20 V/m from 10 to 40 GHz with horizontal and vertical polarization measurements above 30 MHz. If the hardware does not have the shielding protection of a metal fuselage, etc., the field strength test value shall be 200 V/m across the test band.

This test has good and bad characteristics. Incident illumination on interface cables is probably the most reasonable method of detecting IC nonlinear susceptibilities discussed in Section 2.1 as opposed to the time consuming, often uncontrolled, direct injection method. Unfortunately, the screen room test set-up is generally not indicative of the actual system installation and false or misleading results may be obtained. The broad frequency range specified in this requirement is a prime candidate for truncating testing based on tailoring analyses.

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2.4 Overview of Existing Technology, IEMCAP

The Intra System Electromagnetic Compatibility Analysis Program (IEMCAP) is a computerized analysis process/tool designed to facilitate EMC into an electronics system. The objective of IEMCAP is to accomplish the following tasks:

a. Provide a continually maintained and updated data base by incorporating system design changes and by organizing EMC design evaluation and test efforts,

b. Generate EMC specification limits tailored to the specific system,

c. Evaluate the impact of granting waivers,

d. Survey a system for incompatibilities,

e. Assess the effect of design changes on system EMC,

f. Provide comparative analysis results to base EMC trade-off decisions,

g. Determine the adequacy of EMC specification limits.

2.4.1 Analysis Approach

The basic IEMCAP analysis approach is: 1) Model the system in a format compatible with computer analyses, 2) Perform a series of EMI coupling calculations in the frequency domain to determine interference margins between EMI emission levels and susceptibility levels, and 3) Use this data to generate EMC specifications unique to the system.

This approach requires a generated data base which contains a detailed system description, baseline EMI specification limits, and any available EMI test data. The analysis approach is implemented as follows.

2.4.2 System Model

The analyzed system is divided, by the EMC engineer, into subsystem models composed of groups of equipment. Each equipment model is defined as a case containing up to 15 ports, each port being defined as a point where electromagnetic energy may enter or leave. Ports are designated as emitters or receptors or both. An emitter port generates electromagnetic energy and a receptor port is susceptible to electromagnetic energy. Ports within a common piece of equipment are assumed com   le with each other.

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An emitter port is characterized by a broadband power spectral density and/or narrowband power spectra. The spectra is divided into operationally required and non-required frequency regions. Operationally non-required emission spectra are controlled by EMC specifications and can be adjusted by modifying the specs. The operationally required emission spectra consist of signals necessary for the port to perform an intended function (i.e. functional signal) and are therefore not controlled by EMC specifications.

Receptor ports are characterized by a susceptibility threshold curve as a function of frequency. The receptor port has an operationally required and non-required frequency range similar to the emitter port. The susceptibility threshold is controlled by the intended function and by EMC specifications in the operationally required and non-required regions respectively.

The model also includes system geometry, wire and bundle routing characteristics, antenna gain patterns, and filters. This data is utilized by IEMCAP to calculate transfer ratios.

2.4.3 Emitter/Receptor EMI Coupling and Safety Margin Analysis

EMI coupling transfer ratio calculations are performed at the port level of the model. For a selected emitter-receptor port pair, a test is performed by IEMCAP to determine if EMI coupling paths exist. Coupling paths can consist of field or antenna to wire, wire to wire, antenna to antenna, field to antenna, field to case, and case to case. If a path exists, a number of algorithms are used to calculate the transfer ratio. The transfer ratio is defined as the power coupled from an emitter port, through the coupling path, and received by a receptor port.

The power transfer ratio, the emitter power and/or power spectral density, and the receptor susceptibility threshold are then used to determine the "EMI Margin" at each frequency of interest. The two formulas used to calculate EMI margins are shown below:

The Narrowband EMI margin is given by:

$$m_p^N(f_l) = \frac{P_j^N(f_l)\, t_{ij}(f_l)\, r_{ir}}{r_{je}\, S_i(f_l)} \tag{1}$$

where:

$m_p^N(f_l)$	=	Narrowband EMI margin at frequency f_l
f_l	=	frequency of interest
$t_{ij}(f_l)$	=	power transfer function between the j-th emitter and i-th receptor at frequency f_l
r_{ir}	=	i-th receptor input resistance
r_{je}	=	j-th emitter output resistance
$S_i(f_l)$	=	i-th receptor susceptibility in watts
$P_j^N(f_l)$	=	Narrowband power of j -th emitter at frequency f_l

The Broadband EMI margin is given by:

$$m_p^B(f_l) = \frac{w_j^B(f_l)\, t_{ij}(f_l)\, b\, r_{ir}}{S_i(f_l)} \tag{2}$$

where:

$m_p^B(f_l)$	=	Broadband point EMI margin at frequency f_l
$w_j^B(f_l)$	=	Piecewise constant j-th emitter broadband power spectral density (watts/Hz)
$t_{ij}(f_l)$	=	Piecewise constant power transfer function of coupling path between j-th emitter and i-th receptor
b	=	Bandwidth used in calculation of $m_p^B(f_l)$
r_{ir}	=	i-th receptor input resistance
$S_i(f_l)$	=	Piecewise constant i-th receptor susceptibility (watts)

In addition to EMI margin calculations at each frequency of interest, IEMCAP performs two types of integrated interference margin calculations. The first type, designated the "Integrated EMI Margin", represents the ratio of the power received by a receptor port, from each existing emitter port coupling path, to the ports' susceptibility over the entire frequency range. The integrated EMI margin is the sum of narrowband and broadband integrated margin components.

The second integrated safety margin calculation yields the "Total Integrated EMI Margin" which represents the ratio of the power received by a receptor port, from all emitter ports, to the ports' susceptibility over the entire frequency range.

2.4.4 EMC Specification Generation

The IEMCAP specification generation routines adjust the results of the emitter/receptor EMI coupling and interference margin analyses in an attempt to produce a compatible system. This is accomplished by modifying the emitter/receptor port spectra. First, each emitter port's emission spectra in the operationally non-required frequency regions is reduced if an incompatibility was identified in the previous analysis. Next, each receptor port's susceptibility threshold in the operationally non required frequency region is increased, making the port less susceptible if an incompatibility was identified. Since the adjustments are only in the ports' operationally non-required frequency spectrum, and don't represent changes in functional signal levels, the results reflect EMI specifications tailored to the system being analyzed. The amount of adjustment is limited to values selected by the program user.

3.0 ASSESSMENT

The requirement for tailoring contained in MIL-STD-461B, if properly implemented, should remove much of the disparity between MIL-E-6051 and MIL-STD-461. Whereas MIL-E-6051 totally relies on analysis in an unstructured manner and sets no limits, MIL-STD-461 is rigidly structured in test method and configuration as well as limits. Tailoring affords a means for adjusting requirements, as necessary to achieve system compliance thereby lessening the impact of 461's rigidity and lessening it's variances with MIL-E-6051.

Tailoring must be applied from the system perspective, which means the procuring agency or prime contractor will have to perform the analysis and impose requirements on the subcontractors in MIL-STD-461 format (CE, RE, CS or RS). Subcontractors will not have the system information necessary for the analyses, nor will they generally have the staff or means to perform the analysis if the data were made available to them.

Major aspects of a successful tailoring effort must include: (1) reasonably accurate source, coupling, and response models of the system hardware and environment; (2) a real time correlation between hardware and mission events; and (3) a credible computational code for moderate to complex systems. Figure 3.1 illustrates tailoring as closed loop processes - initial requirements based on best case data which are later modified and adjusted as the subsystem and system designs mature.

The principal function of tailoring is to develop meaningful MIL-STD-461 tests and limits for individual subsystems in their relationship to the remaining part of the system. Since this is true for every part of the system, it is hypothetically possible to treat the total system as a subsystem and perform a single MIL-STD-461B test with MIL-E-6051 safety margins as a combined test. Unfortunately, this is unlikely to occur frequently. Procuring ˈgencies, prime contractors, and subcontractors typically administer EMI/EMC in the same manner as other environmental parameters (temperature, vibration, shock, etc.), i.e., definitive parameters with finite limits. Consequently, tailoring will continue for some time to be adminstratively handled as a subsystem in the context of past MIL-STD-461 methods, but technically, tailoring is intended to be a method amenable to change.
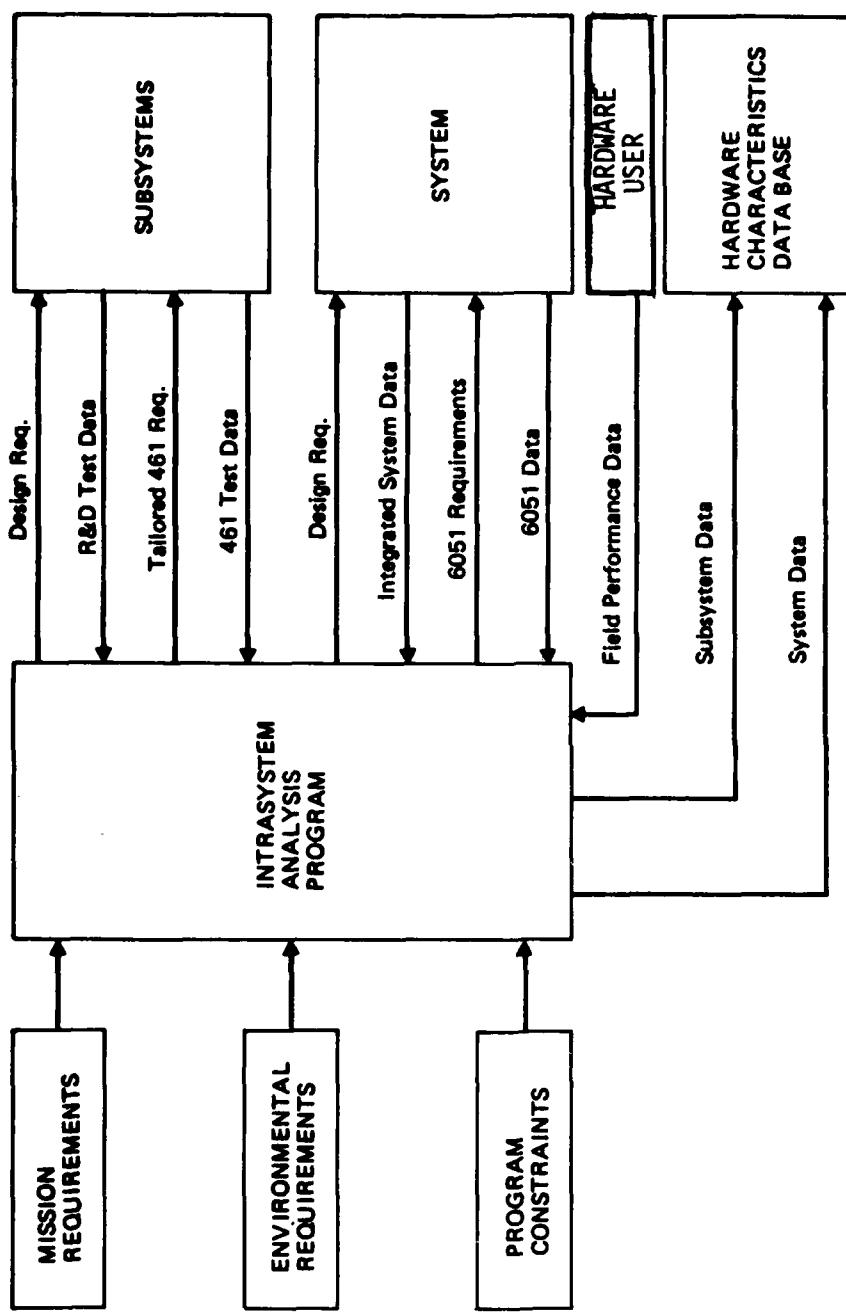
Figure 3.1. Intrasystem Analysis Program Principal Inputs/Outputs

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3.1 Analysis

A system analysis based on the S:C:R concept requires mathematical models to represent the individual source, coupling, response characteristics and their inter-relationships. This is true for both design and test-tailoring purposes.

3.1.1 Source Characteristics (S)

As noted in Section 2 a source element(s) may be an intrasystem component such as a dc-dc converter, discharging relay, fast switching logic circuit, etc., or it may be an intersystem element such as a lightning stroke, nuclear EMP, or high level radiation as may occur from ECM equipment and radar. These latter elements are new EMC control items as directed by Section 1.2 of MIL-STD-461B, Part 1.

Intrasystem sources will generally have a steady state and a transient characteristic which may require more than one model. Several examples will be provided to illustrate this from the physical point of view.

Example 1. A step down transformer is to be used 3 ways.
Case 1 — The secondary side is a resistive load and 100% transformation efficiency is assumed, thus, the input power and output power are equal. The wiring associated with the primary side will represent high voltage and low current sources and the secondary low voltage and high current sources relative to each other. The two sides will have the same frequency but will probably be phase shifted. EM fields will superpose and will be additive or subtractive.
Case 2 — The secondary is centertapped and two diodes are added to make a full wave rectifier. The primary side characteristics remain essentially unchanged but the peak voltage and current of the secondary are halved while the frequency doubles. Superposition of EM fields still applies with the primary an ac field and the secondary a pulsed dc field.
Case 3 — Capacitance is added in parallel with the load resistance to obtain a more steady state dc output voltage. The primary voltage will remain an ac voltage with a slight ripple and the secondary voltage will be a dc voltage with an overriding ac ripple. The primary current will be a pulsed ac current and the secondary current will be a pulsed dc current with both currents less than 100% duty cycles. Current peaks will increase and the waveform can be analyzed as a spectrum of harmonics.

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Example 2 A dc relay is to be controlled by mechanically switched contacts.

Case 1 – At turn on, the line current waveform is determined by the self inductance and resistance of the relay assuming negligible source and line impedance. At turn off, the open contacts of the switch represent a lossy capacitor. (a) If the medium ionizes, the relay will discharge at a rate faster than the charge time; or, (b) if ionization or leakage current is negligible, the capacitive effect takes place and a high frequency LRC oscillator network may result.

Case 2 – A suppression diode is added across the relay coil. The turn on conditions are unchanged from case 1. At turn off (switch opens), the diode becomes forward biased due to the relay discharging and it becomes a shunt path to the external circuit containing the switch. Typically, the diode impedance is much less than the external circuit and it conducts the major portion of the relay discharge current. Because the diodes impedance is small, the relay dropout time is extended over that without the diode. (Pull-in and dropout times should be approximately the same for suppressed coils).

Intrasystem analytical source models should satisfy at least two fundamental requirements. First, they must represent the physical laws involved, and second, their mathematical form should be experimentally verified to be reasonably accurate before applying them in code form.

Intersystem source models for lightning discharges, EMP, helicopter static charge, etc., should meet the same mathematical-physical law and experimental verification criteria set for intrasystem models. However, these are generally physical phenomena that require special test facilities too expensive to develop and maintain in relation to their usage; consequently, the test verification requirement will most likely not be satisfied. If this is the case, then design or application by reason of similarity to situations which have withstood the actual intersystem threat are often used to satisfy the practical requirement. Occasionally, a scaled down system based on proportional analysis may be used to experimentally determine the validity of the analysis.

The margin of error in source modeling or any aspect of the S:C:R relationship should be relatable with the end objective. For example, the typical electromagnetic interference safety margin (EMISM) for MIL-E-6051 is 6dB which requires the constituent parts of the S:C:R equation have errors in the range of 1dB or less. The implication of this condition is that analysis will most probably always require some amount of testing

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for verification or confidence purposes as it is difficult to achieve this accuracy in physical and environmental models for the number of variables involved with electromagnetic fields.

3.1.2 Response Characteristics (R)

Response characteristics are typically represented as receptors containing active elements such as semiconductors or vacuum tubes. However, from the viewpoint of physics, any device which responds to an electrical stimulus can be classed as a receptor, e.g., the relay previously used to illustrate source characteristic dependency on configuration can also respond to EMI if it is of the proper form. Why relays are not thought of as a receptor, can be used to illustrate the make-up of a receptor. The relay requires 2 ports, usually called a power input and a power return; in the realm of electronic devices this is comparable only to the diode.

The response time of a relay is constrained by its time constant which is generally in the upper microsecond to submillisecond range; contemporary electronic state changes are on the order of subnanoseconds, or 5 or 6 magnitudes difference in response times. Small "signal" type relays require power inputs in the mid to upper milliwatt range; discrete digital components power consumption is in the upper microwatt to lower milliwatt range. There is always a fixed relationship between a relay's input and output; active analog devices can be continued to present an infinite number of relationships between input and output.

On a practical basis the general characteristics of a receptor from this discussion are: more than two ports, low power consumption, fixed or variable relationship between input and output, and rapid response between input and output. In addition, the energy storage capability of the relay accentuates it's source capability whereas a typical receptor does not store energy, it is more an information processor.

Typically, an analytical model will contain at least 3 ports - an input power port, an input signal port, and an output port such as a transistor. On the other hand a microprocessor which is physically a single component with hundreds of self contained 3 port devices may have any number of ports. This poses a problem in many situations as to where and how many boundaries are necessary to characterize a receptor or group of receptors. This is where the EMI/EMC community is subject to some criticism. It is not uncommon to apply a filter to an equipment interface because EMI at that interface is

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known to cause a problem. If the matter were pursued to a conclusion of understanding of the complete S:C:R relationship, there are usually alternatives to brute force filtering. Being able to explain and understand the physics of an EMI problem is equally as important as mathematical manipulations related thereto; in fact common sense and experience probably resolves more problems than rigorous calculations.

Response characteristics or receptor models require knowledge as where to set boundaries and how to establish parameters. This is particularly applicable when the concept of critical circuits required by MIL-E-6051 is at issue. MIL-STD-461 constrains all tests to be performed on interface wiring. But what if the critical function or circuit is not an interference wire and is actually buried within the circuitry of a particular equipment? This is the intent of MIL-E-6051's requirement to identify critical circuits requiring an EMISM and restrict the use of breakout boxes, i.e., critical test points should be design features of the system equipment. However, even if this MIL-E-6051 criterion was complied with, MIL-STD-461 has no provisions for including special test methods. Response characteristics are seldom available to the extent necessary to finitely analyze EMI effects if the receptor is more than a single element, such as a transistor. Generally all response characteristics are provided for nominal input power conditions of 5 or 10%, but seldom are they provided for abnormal power conditions. Response characteristics for nominal inputs are generally provided or available but not abnormal input conditions. Response characteristics for EMI applied to an output as often occurs are seldom available except by special test.

Since an analytical or empirical data base may not be available in terms of power, input and output ports, analyses and modeling is subject to considerable error and experimental verification of physical and mathematical interpretation becomes critically important. There is also a tendency to treat only normal mode inputs to a response function as represented by the (e) sources in Figures 2.2 and 2.3 in section 2. There are also common mode conditions when an incident field is simultaneously common to ports that may or may not convert to a normal mode condition.

3.1.3 Coupling Characteristics (C)

Coupling characteristics of a system are largely due to wiring and antennas. Incident radiation on the conponents of a circuit may result in some problems but these situations are usually controlled by enclosure shielding. There are two classes of wires to be considered, signal wires and power wires.

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3.1.3.1 Wire Coupling

There are two types of wire coupling to be considered - common impedance and EM field coupling. Common impedance coupling is illustrated by Figures 2.2 and occurs because multiple currents share a common conduction path. The resistance portion of the path is usually made acceptable by power design engineers in their attempts to provide acceptable input power to user loads. However the power engineer is seldom concerned with the power network-line inductance and that concern is inherited by the EMC engineer.

In addition to the line inductances it is necessary to establish the steady state and transient current characteristics for all power sources and user loads. When these are known an analysis network may be constructed for the system, node voltages calculated and results compared to power interface and signal interface susceptibility thresholds.

Signal line coupling is illustrated on Figure 2.3 by a single voltage generator. This is a common but misleading representation of actual field coupling phenomena. The figure implies a single voltage is induced in the signal network because of magnetic vector - induction loop area. This is a mathematically true statement however the physical phenomenon involved is that all branches of the signal loop experience induced voltage due to magnetic fields and the single generator symbol represents the simultaneous, net result of all branch-field interactions. This situation is generally of no consequence when rms analyses are performed but it will affect digital circuit analysis where leading edge and fast response characteristics of concern. An additionally misleading fact associated with the schematic representation is the implication that electric field coupling is not involved whereas it is just as involved as the magnetic field. Displacement currents will occur between the source wire(s) and signal wire(s) and be a contribution to the EMI level. The end result is that to be reasonably accurate, coupling models must be distributed models with boundary and steady-state values included. This level of analysis is quite complicated and made even more so by the various wire configurations used, i.e., single wire-ground return, wire pairs, shielded and unshielded wires, single and multi grounds, etc. Considerable EMC literature is available to provide deeper insights to this for wire-to-wire and field-to-wire coupling. Caution is advised however as the coupling portion of the analysis can generally introduce more error than either the source or response characteristics because it is a more complicated fields problem and not the simpler circuit problem.

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3.1.3.2 Antenna Coupling

Antenna coupling is a refined extension of the EM field-wire interactions as antennas are no more than special wire configurations. There are considerable data on antenna lobe patterns, frequency selectivity, impedance characteristics, etc, as the antenna discipline was established long ago. In this regard antenna responses can generally be obtained from other than EMC data sources at least in the frequency range of operation; out of band data may have to be obtained for EMC purposes. The antenna lead or wave guide connection to the interface ciruit must be included as part of the coupling characteristics. The technical aspects of antenna most frequently neglected with respect to EMC analysis are minor lobe patterns and multipath coupling each being very dependent on the using systems configuration.

3.2 Tests

MIL-STD-461 requires subsystem or combined subsystem emission and suscep-tibility tests for line conducted and radiated coupling modes. MIL-E-6051 has no system test categories; it only requires that the interference level of a circuit have an Electromagnetic Interference Safety Margin (EMISM) with respect to the level of interference that would cause a malfunction or unacceptable response. Typical safety margin values are: 0dB for noncritical circuits; 0 to some specified value for critical nonordnance circuits but not less than 6dB if unspecified; and, 0 to some specified value for ordnance circuits but not less than 20dB if unspecified.

Prior to MIL-STD-461B, failure to meet test limits was resolvable only by redesign or waiver, the latter justified by analysis that the failure to meet the limits would not be detrimental to the system. MIL-STD-461B's new requirement for tailoring invokes responsibility to establish MIL-STD-461 test categories and limits for subsystems based on the requirements of the system. This tailoring action should eliminate unnecessary MIL-STD-461 testing and cause test performance to be consistent with the MIL-E-6051 objectives; and avoid unnecessary waivers or deviations .

The key word to MIL-E-6051 testing is analysis - which circuits are to be tested, what is the success criteria, how will instrumentation be handled, etc. The key word to tailoring is also analysis - which circuits will be test candidates at the system level, what are the subsystem's design and performance characteristics, do marginal design conditions provide for redesign option within the subsystem and the system, etc.

These tasks are not easily achieved. The requirement that design details be known before they are established means a risk is always involved.

Achieving an effective and efficient EMC test program with tailoring will require the following basic steps.

a. Establish system design criteria based on mission performance requirements, and operational and program constraints.

b. Invoke the system design criteria by specific design requirements on subsystems.

c. Monitor the subsystem and system designs, and preliminary design test data.

d. Perform a preliminary integrated system analysis and issue subsystem test requirements in MIL-STD-461 context.

e. Monitor integrated system electrical problems and progress.

f. Perform a final integrated system analysis incorporating subsystem test data and issue system test requirements in MIL-E-6051 context.

g. Develop a system EMC test data base from preliminary design data (Step c), MIL-STD-461 data (Step d), integrated system data (Step e), and MIL-E-6051 data (Step f).

h. Maintain liaison with field operations for overlooked or new EMC problems and update the data base.

This is a conceptually sound and workable plan but may experience implementation problems for the following nontechnical reasons.

1. It requires a shift of emphasis from test to analysis; many managers and engineers will be uncomfortable with this as typically their experience is test and not analysis oriented.

2. A proliferation of computer codes has occurred to handle particular parts of EMC problems but no single program exists to handle the complete system EMC problem. In addition many codes are unverified or certified for large scale system usage and may introduce errors.

3. The tailoring concept is envisioned as an iterative data exchange process between contracting parties which tends to be self defeating by creating scheduling and contracting difficulties.

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4. Maintaining liaison with the customer after system delivery to investigate possible field EMC problems is a cost burden not normally incurred and may be viewed as an unnecessary venture.

Irrespective of foreseeable shortcomings the task objective is a worthy goal. The remainder of this subsection is directed at new tests, test elimination, and test modifications believed necessary to unify the intent and purpose of subsystem and system EMC tests.

3.2.1 MIL-STD-461 Testing

Section 4.5 "Acceptance Criteria" of MIL-E-6051 states; "Compliance with the specification shall have been achieved when compatible operation, including approved safety margins, is demonstrated without unacceptable responses or malfunctions. If the procuring activity agrees that it is impractical, or not within the contractor's ability to make corrections, minor undesireable responses shall not prevent the system from complying." The cardinal EMC requirement is that the hardware has to perform its intended functions within "agreed" to limitations. It is administratively academic if a MIL-STD-461B CE03 test fails to meet a broadband limit between 30 and 35MHz unless that bit of technical data is shown to be detrimental to the system performance. The first step towards more cost effective EMC expenditures is not elevating MIL-STD-461 test issues above the MIL-E-6051 compatibility requirements. This is principally an administrative issue. The second step is to perform meaningful MIL-STD-461 tests that support the MIL-E-6051 objective and eliminate useless tests. MIL-STD-461's genesis is analog signals using vacuum tube circuits and it is dedicated to the protection of voice radio equipment. The latest version of the specification acknowledges some of the inadequacies, but it retains old test limits and adds some new ones. However, it does make both standards subject to change via tailoring. The new requirement to pursue susceptibility testing to failure thresholds or to pursue susceptibility testing to test equipment limits emphasizes the need for threshold data, but the old limits and methods remain in use. Source characteristics can generally be measured or estimated, coupling can generally be calculated or measured, but suceptibility, because it is principally an abnormal condition, is almost invariably a test consideration until a meaningful data base is established. It is therefore concluded that susceptibility thresholds are the most important data to be obtained from MIL-STD-461B testing; susceptibility thresholds are critical to system analysis and system test. The CE, CS, RE and RS tests presented in Section 2.3 will now be discussed regarding their use in support of system level tests with

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the acronymn TBD representing "to be determined" values based on the system under consideration.

CE01 and CE03

There is a need to add a broadband test requirement for CE01 and set upper frequency test limits for broadband and narrowband tests at the TBD harmonic for AC power and TBD harmonic for DC power when converters are used. Initial amplitude limits are to be tailored based on subsystem power budget allocations and the type of power source; final amplitude limits are to be established based on system accumulative loads, power source characteristics, power distribution, and the control network. The upper frequency test limit shall set the lower frequency test limit for RE tests.

The intent of this test is to provide load spectral data for assessing power source compatibility, calculating power common-signal common voltage drops, and calculating magnetic field coupling situations as necessary. It is presumed that, except for transient loading conditions, the voltage changes will remain within nominal tolerances. Should system voltage levels be required to predict MIL-6051D test parameters, the measured currents, in conjuction with system distribution network design data, can be used to acceptably estimate the voltage characteristics of the system using transmission line theory.

CE06

Tentatively retain this test in its present form but survey industry and government specifications for requirements that may lessen or eliminate the test.

CE07

Aircraft electrical power system requirements, controlled by MIL-STD-704D, sets 115V rms transient limits at +56% and -30% for 10 ms then linearly decreasing to +7% (nominal) at 80 ms, and, +28 vdc transient limits at +78% and -36% for 15 ms linearly decreasing to +3.5% at 82.25 ms and -21% at 100 ms except as modified by MIL-E-6051. MIL-E-6051 sets spike (transient) limits at 50 us duration and +50% for AC power lines and +50%, -150% for DC power systems. MIL-STD-461B, Part 2 (5.1) applies the latter requirements to power sources and load equipments without exception, i.e., aircraft and nonaircraft.

It is presumed the intent of the MIL-E-6051 requirement is mainly to control relay discharge effects because of the -150% DC limit, particularly since the MIL-STD-704, a MIL-E-6051 requirement, upper amplitude limits are +56% and +78% for AC and DC systems, respectively; both limits are greater than the +50% requirement of MIL-STD-461B. Power line transient limits can practically be based only on system design and the method of load control and distribution.

This test should be replaced with two tests to evaluate power source and load surge transient characteristics. Simultaneous current and voltage measurements should be made at the UUT power terminals.

a.   Load turn on and turn off transients would be measured; AC load turn on would be synchronized at 0^c, 45°, and 90° phase relationship with the applied voltage.

b.   All power sources would be subjected to load change tests of 10% to 100%, 100% to 10%, and 10% to TBD to 100%. The 10% and 100% loads should be resistive and the TBD load should be a resistance-capacitance load with a time constant based on system rationale.

CS01

This test as presently conducted, series injects interference simulating induction pickup by a power line loop. Assuming wire pair design with the wires separated 0.1 inches as the pickup loop and 10 meters of coupling with a 60 Hz source isolated wire, 2000 amperes would be required to generate the 5 volts required by the test. Any situation allowing this has absolutely no design control; conversely systems with design control would not benefit from the test. This test should be eliminated and replaced with the following test to simulate parallel load switching currents over a common powerline.

Connect a load in parallel with the UUT at the end of a power cable (which is TBD meters in length) to the power source. The parallel load shall have a rectified current wave with a TBD duty cycle for AC power and shall have a switched current waveform with a TBD duty cycle for DC power with load ranges of 100 to TBD% of the UUT. The parallel load value shall be increased while observing the UUT's performance; if malfunction occurs, obtain UUT power terminal voltage and current waveforms as threshold data. The TBD values are to be tailored based on the system's power distribution network design.

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CS02

This test should be eliminated as RS testing will provide powerline and signal line susceptibility results.

CS03, 04, 05 and 07

Investigate industry and government specifications for possible consolidating or eliminating these tests in conjunction with the CE06 study.

CS06

This test can and should be eliminated for systems with EMC design control as it attempts to simulate inductive discharges which will not exist. The characteristics of the test imply a solenoid discharging into a high impedance which will not be the case because of diode suppression, switch arcing, transmission line impedance, and power source impedance.

CS09

This is a Navy test and will not be critiqued.

CSXX

This is a test which does not presently exist but should be added for digital circuit interfaces to assure there is insufficient crosscoupling, between signal wires over a TBD interface distance, to cause functional problems. The test should reasonably duplicate the system design and should be required unless it is shown that crosscoupling is not a performance concern.

RE01

This test should be retained but the upper frequency limit should be set at the RE02 lower frequency limit. It is immaterial whether the data is acquired by electric or magnetic field measurement.

RE02

        This test should be retained but it should be performed without cable and wire shields except when the signal wiring requires twinax, coax, or individual wire shields. The intent is to acquire the emission spectrum of the UUT and cabling in its purest form and apply the system level wiring, cabling and shielding controls deemed necessary. The upper frequency test limit should be not less than the TBD harmonic of the highest frequency or repetition rate generated by the UUT.

RE03

        This test should be evaluated in conjunction with the CE06, CS03, 04, 05 and 07 study on rf systems.

RS01

        This test should be retained up to the lower test frequency limit for RS03.

RS02

        Retain this test but run the source wire parallel with cables to represent a structure system for power/control lines.

RS03

        Retain only the 200 v/m test requirement but use cables as described for RE02. The intent is to obtain susceptibility threshold data and not necessarily meet the 200 v/m requirement. After the spectrum threshold data has been acquired apply the equivalent of system shielding methods and repeat the test to establish the prescribed shielding's effectiveness. Perform a CW and pulsed CW tests.

        The commentary for CE01 through RS03 presumes the equipment tested has a specific use for a specific system and presumes the system will have an end-to-end EMC program.

3.2.2 MIL-E-6051 Testing .

MIL-E-6051, Section 3.2 states; ".... Every effort shall be made to meet these requirements during initial design rather than on an after-the-fact basis...". Compliance with this condition requires EMC engineering be actively involved in the initial design phases for the system as well as the subsystems. Concurrent with this involvement, the EMC staff should identify those functions which are (or likely to be) Category I and II and which require tests to show a positive safety margin. Assuming this has been done and that the identified functions are not accessible by test points (for other reasons), effort should be made for accessibility which will have minimum impact later on in the MIL-E-6051 test. This action is desireable as Section 3.2.3.1 on safety margins specifies that existing test points are to be used and breakout boxes are to be minimized; this approach is taken so that production systems may be tested with a limited EMC test to verify that redesign and retrofits do not invalidate the first article EMC validation test. One hundred percent test point accessibility is seldom possible, particularly if current probe measurements are needed, however, it is a desireable goal and should be implemented to the extent possible. As the subsystem and system design matures, hardware performance and problem data should be analyzed for probable EMI and Category I and II classifications and modified accordingly with emphasis placed on eliminating as well as adding test candidates.

The electromagnetic interference safety margin (EMISM) concept presumes a susceptibility threshold and an in-circuit EMI value are both known so their decibel relationship can be computed. However as noted previously, susceptibility characteristics (if they are to be determined at all) will generally have to come from MIL-STD-461 tests except possibly for analog signal circuits where linear analysis can be applied. Power line, digital circuit cross coupling, IC rf nonlinear detection, and ground current susceptibility modes are all abnormal performance conditions that may have to be determined empirically. If actual thresholds are not established the actual test limits will have to be considered as boundary conditions. The net result is that safety margins cannot be set until the hardware has been tested to MIL-STD-461 which may be a considerable time after the initial design phase.

Typically 6dB and 20dB EMISM's are respectively applied to nonordnance and ordnance circuits, however, these are the mimimum MIL-E-6051 acceptable values in lieu of other values not specified in the EMC control plan. The actual SM value should be based on the affected function and its relationship to the mission. For example an

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electrical transient corresponding to a 5° guidance offset in the early flight of a missile may very well be a tolerable situation, but the same transient in a terminal guidance phase is usually intolerable. Or a saturated logic signal of 0.2vdc may tolerate a level change up to 1.2 volts but this does not necessarily mean the safety margin is 14dB.

Comparing circuit susceptability data from a subsystem, MIL-STD-461 test to the interference level measured in a MIL-E-6051 is a one-to-one relationship and the direct approach for determining SM. However, there are alternative schemes based on the following reasoning. A circuit which performs its intended function without adverse EMI effects has at least a 0dB, and probably a positive, safety margin. If the effects of interference which is present are enhanced to a given amount and normal operation continues, then the safety margin is at least the equivalent of the enhancement. Theoretically, it is possible to increase S, increase C or decrease R and attain a EMISM. Increasing S implies an injection process requiring an active source but this may endanger system components. Increasing C can be done in a passive manner, such as adding line inductance to a power line or using an injection scheme that drives the continuity loop or spare wires in cables. This will provide a tight coupling with the wires of the same cables; a closed loop will cause magnetic field coupling and an open loop will cause electric field coupling. Decreasing R can be accomplished by altering the circuit bias, or input impedance, to enhance EMI effects. One injection scheme, which has merit and can be implemented with minimimal danger, is to drive the continuity loop used in some systems.

3.3 IEMCAP Assessment - Task Flow and Problem Areas

An EMC program utilizing the IEMCAP methodology must, from project initiation, tailor its test program to support IEMCAP. The test program must include a circuit level testing component, as well as subsystem and system level EMC tests. Ideally, circuit tests are performed as the analysis models are being developed, providing empirical data to supplement the specification data and physical system parameters which make up the models. The results of the IEMCAP analysis are then used to assist in selecting system test monitor points. The number of test monitor points can be reduced to a minimum where system tests are performed only to validate IEMCAP results. Data should be gathered in areas which have been identified as marginal by IEMCAP; safety margins should be assessed on critical circuits.

Thus, one of the advantages of using IEMCAP is that EMC system test efforts can be minimized. This is a very important advantage since system EMC tests are usually very expensive and time consuming. However, before IEMCAP results can be used as justification for minimizing EMC system test efforts, the entire system must be analyzed for compatibility and a high level of confidence achieved in the analysis.

The task flow for a typical IEMCAP application is shown in Figure 3.2. This figure is reproduced the from IEMCAP user's manual engineering section (RADC-TR-74-342, Vol. I, Dec. 1974). As indicated in the figure, the IEMCAP methodology must be applied early in a system's development in order for its objectives to be accomplished. More specifically, in order for a design to be tailored for EMC performance and in order for system EMC test efforts to be minimized, usable IEMCAP results must be available as design decisions are being made.

The task flow can be divided into three basic tasks: data collection, model development, and output interpretation. These tasks and problems of accomplishing them using the current version of IEMCAP and its methodology are described below.

The first task in the IEMCAP methodology involves the collection of data. This data includes not only physical and electrical design parameters but specification limits imposed on the system under analysis.

Experience has shown that during the initial data collection phase, the following problem areas become evident:

a.   Equipment design, antenna locations, and apertures (such as, thermal blanket gaps, access doors, non-"EMI proof" bulkheads, etc.) may not be finalized because these are a function of more than just EMC considerations. Although, IEMCAP can be utilized to assess/avaluate the different design, these items drastically affect the IEMCAP model by changing the transfer ratios and by allowing/disallowing EMI coupling paths in the model.

b.   Wire routing and power subsystem design may not be finalized for the initial analysis and may be evolving faster than the IEMCAP analysis flow, making the initial analysis iteration obsolete by the time results are available.
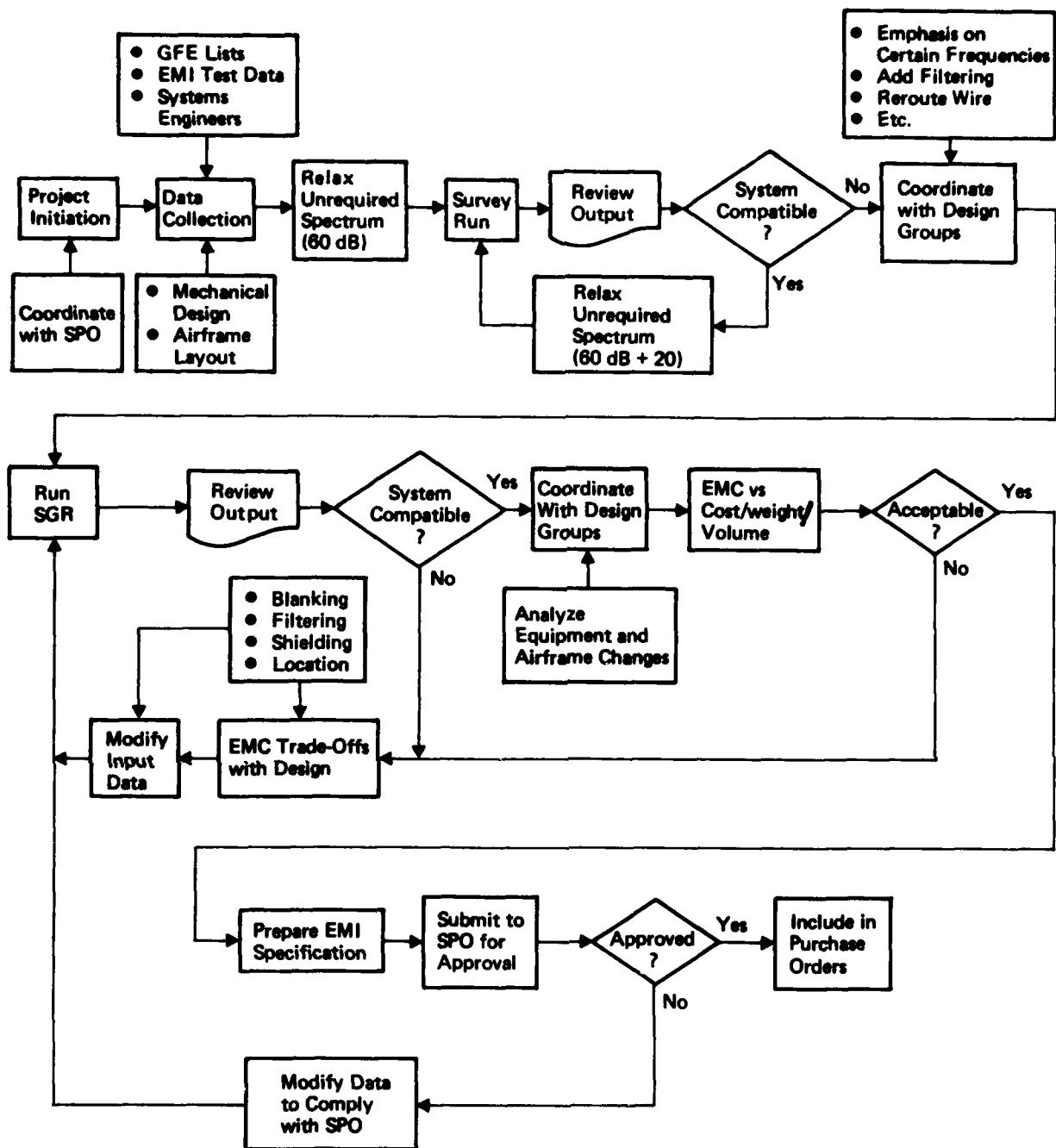
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Figure 3.2: IEMCAP Typical Task Flow (Initial Specification Generation)

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c. EMI test data on GFE may not be available, especially data compatible with IEMCAP input requirements.

d. Equipment level EMI test data is usually not available during the initial data collection phase thus requiring that baseline EMC specifications be utilized in the model as assumed emission and susceptibility limits. As the equipment level EMI emission and susceptibility data becomes available it must be incorporated into the model to provide confidence in the results.

e. Component level EMI test data may be used to determine susceptibility thresholds or emission levels. If the test data is not available then manufacturers specifications may be used. However, in either case, the data must be analyzed to insure that the effects of the implementation method used in the specific system being assessed is considered.

These problem areas are data deficiency related and will exist for any EMC analysis performed early in a systems development. Since the IEMCAP analysis is based on detailed system design parameters, which are not always available until the design matures, an inherent time phasing problem develops between when the output results are required and when the necessary input parameters are available. For this reason, IEMCAP results may be most effective as a tool to reduce the need for system EMC tests and to identify potential incompatibilities. However, IEMCAP can also be used as a specification generator or design aid.

3.3.2 Model Development

The model development task (not shown in Figure 3.2) is equally as important as the data collection task. The confidence in the analysis model is dependent upon the strategies of the program user in developing a model which accurately represents all EMC interactions.

Developing a credible IEMCAP compatible model of circuits has, in Boeing's experience, been a major difficulty in accomplishing the model development task. Specifically, it is not clear that IEMCAP's circuit model consisting of a voltage source, a source resistance and a load resistance as shown in Figure 3.3 is a valid representation for all circuit types. Additionally, it is not clear that IEMCAP's wire-to-wire and field-to-wire coupling algorithms are valid for all emission/susceptibility modes and circuit configurations.

For example, differential circuits, which are susceptible to both common mode currents and differential mode currents, are not easily represented in an IEMCAP model. The IEMCAP model allows only a single load resistance, source resistance, and receptor susceptibility threshold for each circuit. Circuit safety margins, with respect to common mode and differential mode noise, are very difficult to determine based on the IEMCAP model and the results of the IEMCAP analysis. Other circuits, such as three and four wire signal networks and power networks, where multiple loads share common wiring, are not easily modeled within IEMCAP constraints. IEMCAP user's documentation does not contain application techniques which would help the program user to model general circuit types and would help in interpreting IEMCAP results.

A study effort is required which would resolve this problem and would result in a definitive approach to modeling all common circuit types. The results of the study would be used as a modeling aid for IEMCAP users and would provide confidence to the users that the results obtained are valid for the types of circuits being analyzed. This study would consist of three phases as follows:

a. Determination of all generic circuit types (power and signal), their IEMCAP compatible model equivalent, and their emission/susceptibility modes;

b. Further and more complete validation of the IEMCAP models through comparisons of IEMCAP calculations with empirical results (IEMCAP calculations and laboratory
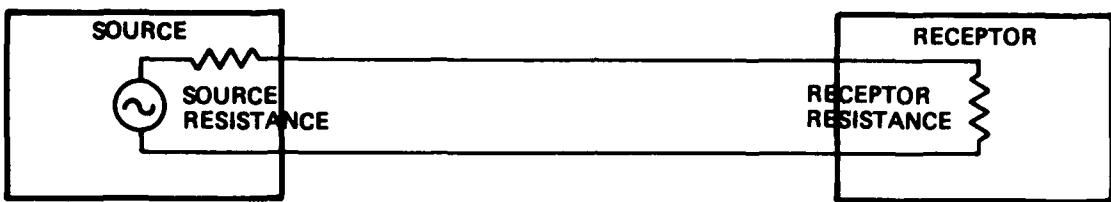
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Figure 3.3: IEMCAP Circuit Model

measurements made for each unique pair of circuit types; i.e. type one coupling to type one, type one coupling to type two, type two coupling to type one, etc.);

c.   Development of a user's manual annex which presents modeling techniques that guarantee accurate characterization of the generic circuit types and emission/susceptibility modes. The user's manual would also contain the results of the first two phases of the study such that an IEMCAP user would have access to typical IEMCAP calculations for each of the generic coupling types. This manual, which would clarify circuit modeling techniques and susceptibility spectra characterization, would compliment the RADC technical report "A Summary of Required Input Parameters for Emitter Models in IEMCAP" (RADC-TR-78-140 dated June, 1978), which clarifies emission spectra characterization for IEMCAP users.

Other problems encounted during the model development task are described below:

a.   The IEMCAP input data requirements lack the flexibility to allow the program user to specify, in the frequency domain, specific emission or susceptibility spectra for signal/control lines, EEDs, and RF ports in the operationally "non-required" frequency region.

b.   Most of the units required for input data to IEMCAP are inconsistent with common EMC test and specification data.

c.   Since the maximum model size in each IEMCAP run is limited by IEMCAP design, a typical system must be represented by several submodels in order to be totally represented. Additionally, since the submodels are analyzed separately by IEMCAP, electromagnetic interactions between elements of different submodels are not assessed. Therefore, the ultimate accuracy and confidence of the analysis results are determined by the skill of the analyst in choosing how the system model will be divided.

d.   Even though a typical system model is divided into submodels to facilitate analysis by IEMCAP, each submodel cannot contain all elements of its portion of the system. This is because of additional IEMCAP limitations. For example, each piece of equipment analyzed by IEMCAP is represented by an equipment model which may contain no more than 15 ports. A typical piece of electronic equipment, however,

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contains many times this number of ports. In fact, many electronic systems contain equipment with an excess of 15 connectors, each containing 15 circuits or more. This limitation forces the program user to use judgment in selecting what will or will not be included in the model and what will be analyzed by the computer. In order for the analysis to predict incompatibilities, the selection must include the equipment's worst offenders (i.e. the worst emitters and most susceptible receptors). Accuracy and confidence in the analysis model is thus dependent upon the program user's skill in selecting model elements.

e.   A portion of the model development task includes the layout of model geometry, the assignment of IEMCAP compatible identifiers for each model component, and the coding of computer cards per the user's manual usage section. A degree of ingenuity is required in order to develop geometrically accurate IEMCAP compatible models of all Air Force system types (i.e. aircraft, spacecraft, and ground system), particularly when antenna to antenna or antenna to wire coupling is included as a part of the analysis model. IEMCAP has the capability to account for RF shading and diffraction due to wings and propagation around a cylindrical fuselage. Therefore, it is very important that antenna and aperture locations are accurately located within the model so that accurate transfer functions may be calculated by IEMCAP. IEMCAP does not contain the capability to display model geometry in any way, except by a tabular format. No easy method exists to verify that the model visualized by the program user is coded correctly in the input data. Extreme care and detailed bookkeeping techniques are required by the program user to assure that the model is error free.

The problems encountered during the model development task are related to incompatibilities between IEMCAP and available EMC data, or are related to IEMCAPs software limitations, and/or minimal user orientation. These problems can be minimized or eliminated by making appropriate software/users manual changes to IEMCAP.

For example, problem number 1), the IEMCAP input data requirements lack of flexibility for specifying emission and susceptibility spectra are summarized in table 3.1. The emission and susceptibility spectra submodels for each port may be developed by describing up to 10 user supplied frequency/amplitude points (called SPECT in IEMCAP terminology), by internal models, or by default levels. However, the input data requirements do not allow the SPECT user specified spectra option in describing operationally non-required frequency region emission and susceptibility thresholds for RF, signal/con-

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Table 3.1 Emission and Susceptibility Spectra Characterization

Port Type	Operationally Required Region		Operationally Non-Required Region (Before Adjustment by IEMCAP Spec Generation Routine)	
	Emissions	Susc. Threshold	Emissions	Susc. Threshold
RF	SPECT or internal emission model	SPECT or constant at minimum sensitivity level	Automatic default to MIL-STD levels $\pm$ initial displacement factor	Automatic default to MIL-STD levels $\pm$ initial displacement factor
Signal/Control	SPECT or internal emission model	SPECT or constant at 20 dB below the operating voltage or current level	Automatic default to MIL-STD levels $\pm$ initial displacement factor	Automatic default to MIL-STD levels $\pm$ initial displacement factor
Power Lines	User specified voltage at power frequency only	20 dB below the operating voltage at power frequency only	SPECT or default to MIL-STD levels $\pm$ initial displacement factor	SPECT or default to MIL-STD levels $\pm$ initial displacement factor
EED	No required frequency region	No required frequency region	N/A	Automatic default
Case	No required frequency region	No required frequency region	SPECT or default to MIL-STD levels $\pm$ initial displacement factor	SPECT or default to MIL-STD levels $\pm$ initial displacement factor

Note: SPECT—IEMCAP term for user supplied amplitude/frequency spectra
Initial Displacement Factor—User supplied deviation of amplitude, constant over entire spectra

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trol, and EED ports. This means that if specific out of band emission or susceptibility spectra is available, this data cannot be used directly in IEMCAP.

If the entire spectrum is defined as "operationally required" so that the SPECT option can be used to describe the out of band emissions, the IEMCAP specification generation routine and IEMCAP's specification tailoring capability is inhibited. This occurs because specification tailoring, by definition, can be accomplished only over the "operationally non-required" frequency region which is controlled by EMC specifications.

Additionally, IEMCAP automatically defines the operationally required frequency region susceptibility threshold as a level 20 dB below the normal operating voltage of the circuit for all power circuits. No provisions are provided to allow the program user the ability to specify a known susceptibility threshold. It is possible to "fool" the program into specifying the proper threshold by developing a model with an operating voltage 20 dB above the known susceptibility threshold. However, this approach reduces IEMCAP's usefulness as a data base since the operating voltage specified does not represent the true operating voltage, but only represents a level 20 dB above the susceptibility threshold.

Another example, problem number 2), is the IEMCAP input data inconsistency with EMC data. These inconsistancies are described in table 3.2 which includes all MIL-STD-461A tests and delinates areas of non-compatibilites with IEMCAP. As indicated, nearly all MIL-STD-461A test data is not directly compatible with IEMCAP. Since IEMCAP is an intra system analysis and is intended to provide a system EMC data base, common equipment and subsystem level test data provided by these tests should be compatible with IEMCAP input requirements so that the system model reflects all applicable EMC data. In order for the model to include this data, it should be possible to specify both required and non-required frequency region emission and susceptibility levels. This would not only make the model more accurate, but it would make the data base more complete.

The problems identified for CE05 and CE06 are examples of IEMCAP spectra inconsistency with test data or the necessity of assuming that repetitive noise is continuous in the IEMCAP model. Where these problems are related to spectra inconsistencies, they do not warrant modification of IEMCAP's analysis approach.

These problems reduce IEMCAP's usefulness and flexibility but can, for the most part, be eliminated without major changes to IEMCAP software or methodology.

Table 3.2 Compatibility of IEMCAP with MIL-STD-461A
Equipment and Subsystem Test Data

Tests	Compatibility With IEMCAP Input Data Requirements

MIL-STD-461A

CE-01, Conducted Emissions, 30 Hz to 20 kHz, Power Leads

IEMCAP requires the input data to be specified in units of dBW/Hz. CE-01 test limits are in units of dBuA and dBuA/MHz, therefore, CE-01 test data cannot be input directly into the code to describe power line operationally non-required frequency region ripple or noise spectra. It may be possible for the program user to use the test data by making the proper conversions involving an impedance and/or bandwidth. However, the broadband test data may be directly compared to the IEMCAP emitter spec level identified in the IEMCAP printout as these units are compatible.

CE-02, Conducted Emissions, 30 Hz to 20 kHz, Control and Signal Leads

The following must be considered before CE-02 test data is used as an input for signal line conducted emissions in IEMCAP: 1) Operationally non-required emission spectra cannot be program user supplied for signal lines, therefore, CE-02 test data at operationally non-required frequencies cannot be used as an input to IEMCAP; 2) IEMCAP requires the signal line emissions to be specified in units of dB uA/MHz, therefore, CE-02 narrowband data cannot be input into IEMCAP directly; 3) CE-02 tests are performed at the wire bundle level, resulting in a composite common mode current. Common mode coupling is considered by IEMCAP only if both the generator circuit and the receptor circuit are not a twisted wire pair, therefore, CE-02 levels are not compatible with IEMCAP if the model contains twisted wire pairs.

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Tests	Compatibility With IEMCAP Input Data Requirements
CE-03, Conducted Emissions, 20 kHz to 50 MHz, Power Leads	Same as CE-01
CE-04, Conducted Emissions, 20 kHz to 50 MHz, Control and Signal Leads	Same as CE-02
CE-05, Conducted Emissions, 30 Hz to 50 MHz, Inverse Filter Method	CE-05 measurements are used only for single event transients or for repetitive noise with repetition rates up to 5 p.p.s. Therefore, if CE-05 data is to be used as input data for IEMCAP, it must be converted to equivalent broadband emissions and it must be assumed that the interference is continuous. This assumption, however, could result in an overly worst case emission model for certain applications.
CE-06, Conducted Emissions, 10 kHz to 12.4 GHz, Antenna Terminal	CE-06 broadband test data may be input to IEMCAP directly to specify RF port operationally required frequency region emissions. However, the test data cannot be used to describe the operationally non-required frequency region because user specified spectra is not allowed by IEMCAP data input requirements in the operationally non-required frequency region. CE-06 narrowband emission measurements are not compatible with IEMCAP RF port emission input data requirements because user specified spectra must be in units of dBm/MHz.

CS-01, Conducted
Susceptibility,
30 Hz to 50 kHz,
Power Leads

CS-01 test data is measured in volts and is not directly compatible with IEMCAP. User specified ripple and noise susceptibility spectrum input data requirements are specified in dBW/Hz.

CS-02, Conducted
Susceptibility,
50 kHz to 400 MHz,
Power Leads

Same as CS-01

CS-03, Conducted
Susceptibility,
30 Hz to 10 GHz
Intermodulation,
Two Signal

Test is not compatible with IEMCAP. It is not desirable for IEMCAP to address intermodulation. This area is better addressed by codes which are specialized for this purpose.

CS-04, Conducted
Susceptibility,
30 Hz to 10 GHz
Rejection of
Undesired Signals
at Input Terminals
(2 Signal Generator
Method)

The CS-04 test determines the susceptibility threshold of a receiver in the operationally non-required frequency region. Currently, IEMCAP input data requirements allow user specified spectra only in the operationally required frequency portion of the spectrum. Therefore, CS-04 test data is not compatible with IEMCAP unless the entire frequency spectra is considered "operationally required".

CS-05, Conducted
Susceptibility,
30 Hz to 10 GHz,
Cross Modulation

Test is not applicable to IEMCAP. It is not desirable for IEMCAP to address cross modulation. This area is better addressed by codes which are specialized for this purpose.

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Tests	Compatibility With IEMCAP Input Data Requirements
CS-06, Conducted Susceptibility, Spike, Power Leads	Test is for transient susceptibility, and is not directly compatible with IEMCAP since IEMCAP does not address transients.
CS-07, Conducted Susceptibility, Squelch Circuits	The following items must be considered before CS-07 test data may be utilized as input data for IEMCAP: 1) The squelch circuit cannot be sensitive to the rise time or peak voltage of the impulse generator, 2) the squelch circuit must be average power sensitive, 3) the equivalent impulse power must be converted to average power as a function of frequency, 4) the resultant average power must be converted to a narrowband current.
CS-08, Conducted Susceptibility, 30 Hz to 10 GHz, Rejection of Undesired Signals at Input Terminals (1-Signal Generator method)	Same as CS-04
RE-01, Radiated Emissions, 30 Hz to 30 kHz, Magnetic Field	IEMCAP does not address magnetic radiated emissions or susceptibility. Since magnetic field problems are most often addressed by designers at the component level and problems at a system level are rare, it would not be especially useful to modify IEMCAP to analyze this effect.

Compatibility With IEMCAP
Input Data Requirements

RE-02, Radiated
Emissions, 14 kHz
to 10 GHz,
Electrical Fields

RE-02 test data may be used directly to describe equipment case leakage for both broadband and narrowband emissions. In addition, RE-02 narrowband data may be used to describe environmental electromagnetic fields.

RE-03, Radiated
Emissions, Spurious
and Harmonic
Emissions, 10 kHz
to 40 GHz

The RE-03 test data for the operationally unrequired RF port emissions is measured in units of watts. IEMCAP RF port emissions can be user specified only for the operationally required frequency region, and user specified spectra must be in units of dBm/MHz. RE-03 test data are not directly applicable to defining IEMCAP environmental electromagnetic field parameters, which must be specified in dBv/m.

RE-04, Radiated
Emissions, 20 Hz
to 50 kHz,
Magnetic Field

Same as RE01.

RE-05, Radiated
Emissions, 150 kHz
to 1 GHz, Vehicles
and Engine Driven
Equipment

RE-05 test data may be used to specify broadband equipment case leakage in IEMCAP. However, the test results are in units of dB uV/m/MHz, which is inconsistent with the units that are used to specify narrowband equipment case leakage, environmental electromagnetic fields, and RF port emission models in IEMCAP.

RE-06, Radiated Emissions, 14 kHz to 1 GHz, Overhead Power Lines	Same as RE-05
RS-01, Radiated Susceptibility, 30 Hz to 30 kHz, Magnetic Field	Same as RE01.
RS-02, Radiated Susceptibility, Magnetic Induction	Same as RE01.
RS-03, Radiated Susceptibility, 14 kHz to 10 GHz, Electric Field	RS-03 test data is consistent with IEMCAP data input requirements for specifying equipment case radiated susceptibility to a narrowband environment.

3.3.3 IEMCAP Output Interpretation

Once all necessary data has been collected and analysis models have been developed, an IEMCAP survey run is performed and IEMCAPs output data is interpreted. However, before commitments can be made to change a system's design based on the analysis, the accuracy of the results should be verified. The verification may be performed by test, further analysis, or by judgement based on similar design or application. Problems encountered during the data review task are as follows:

a. The IEMCAP output is extremely long and contains data redundancy. The tabular format of the output data does not depict spectral data as a plot/graph. Therefore, it cannot reasonably be used in a technical report.

b. A detailed breakdown of the transfer function is not available from the output data. This information would be useful in determining the effects of each contributing

element of the transfer function. For example, the effects of a shield or a pigtail termination on the transfer function should be known before EMC trade-off decisions are made concerning a wire to wire coupling problem.

The tabular output format utilized by IEMCAP is very inefficient because it requires an excessive amount of engineering time to interpret the output data. The output data format should be revised such that the results can be quickly assessed (i.e. plot or graph), and should contain sufficient information for trade-off analyses.

In order to accomplish this objective, the following information (as a minimum) should be available in the output:

a.   A plot, as shown in Figure 3.4, which contains the receptor susceptibility threshold and the product of the emitter emission level and transfer function (ratio). If any bandwidth factor is considered a part of the transfer ratio, the curves share common units and are plotted as a function of frequency. The difference between the two curves represents the safety margin.

b.   A plot of the emitter emission level as a function of frequency.

c.   A plot of the transfer ratio as a function of frequency and a detailed breakdown of each contributor to the transfer ratio.

With this output information and format, a program user can easily and quickly identify problem areas (incompatibilities), excessive and, therefore, inefficient safety margins, and potential resolutions for problem areas.
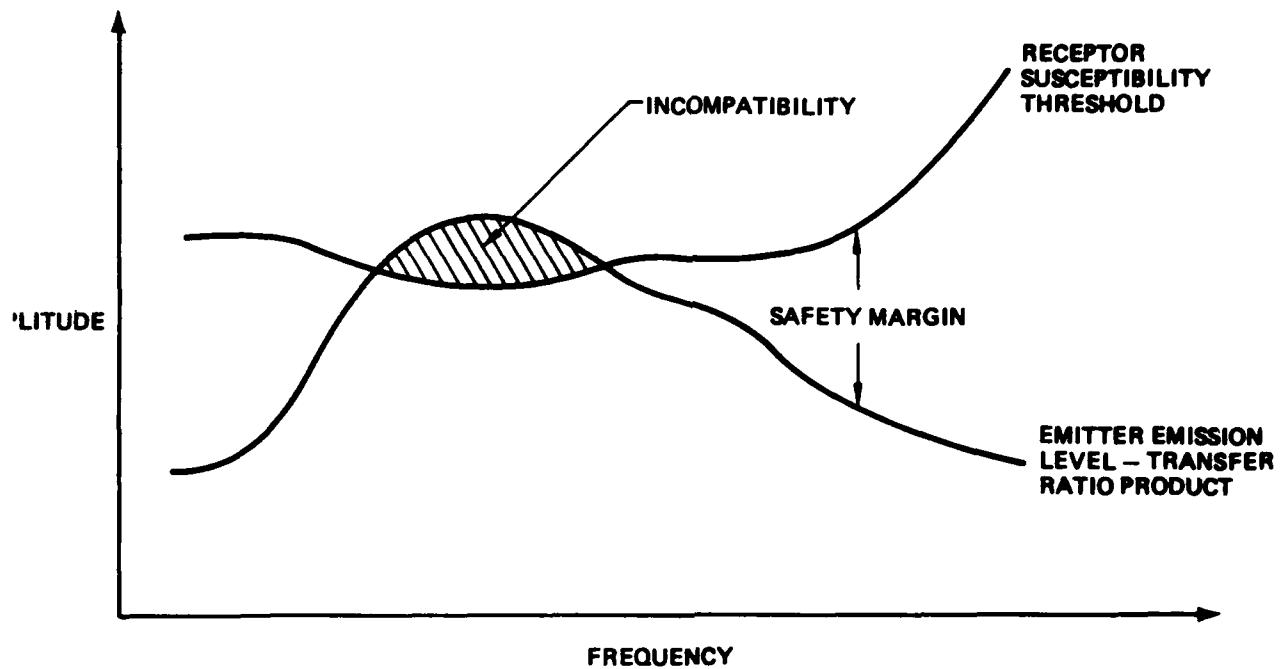
Figure 3.4: Proposed Plot for Inclusion in IEMCAP Output

3.3.4 Coupling Models

The following is a brief discussion of the adequacy of the existing IEMCAP coupling models and the need for new coupling model capabilities.

3.3.4.1 Existing Coupling Models

3.3.4.1.1 Case-to-Case and Field-to-Case

Both case-to-case and field-to-case coupling models in IEMCAP are considered unnecessary. In both models, the radiated susceptibility of the case circuits is assumed to be defined by military standards. In fact, susceptibility is nearly always determined by the circuits within the case which are tied to external wiring. Typically, susceptibility via case penetration would be exceeded by radiation coupling onto external wires and the resultant current conduction into case circuitry. This is reflected in MIL-STD-462 which requires that equipment being tested for radiated susceptibility be configured with interconnecting cables, assemblies, and structures simulating the actual installation of the equipment. The EMC analysis being performed with the case-to-case and field-to-case coupling models can be better performed by using some of the other coupling models contained within IEMCAP.

3.3.4.1.2 Wire-to-Wire

The wire-to-wire coupling models contained within IEMCAP represent most of the commonly used wiring configurations and are considered adequate when only worst case results are desired. However, when IEMCAP results are used to optimize a system design (i.e., used to determine if a single wire structure return can be used instead of a two wire circuit, or used to determine if shields may be removed without system degradation), the wire-to-wire coupling models may produce a result which is overly worst case. For example, because of the approximation of a twisted wire pair by two single wires over a ground plane, which is used in the IEMCAP twisted pair model, the predicted coupling to a twisted wire pair is overly worst case, particularly when low values of terminal load resistances are required. These overly worst case predictions could result in system over-design.

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The proposed study effort, described in the Model Development section of this report, defines in detail the limitations of the wire-to-wire coupling routines and indicates which models require updating.

3.3.4.1.3 Antenna-to-Antenna and Field-to-Antenna

The antenna-to-antenna and field-to-antenna coupling models contained within IEMCAP do not account for losses or gains which occur in any RF system due to antenna and RF cable frequency dependence. The frequency dependence can provide either attenuation or gain to out-of-band signals which enter or leave an RF system through an antenna port. This attenuation or gain is, therefore, a contributor to any intentional attenuation or gain provided by RF filters and amplifiers.

Where the RF cable and antenna provide more attenuation at out-of-band frequencies than is provided at in-band frequencies, a transmitter would create a lower spurious emission interference environment and a receiver would be less susceptible to an out-of-band interference environment. Conversely, where the RF cable and antenna provide more gain at out-of-band frequencies than is provided at in-band frequencies, a transmitter would create a higher spurious emission interference environment and a receiver would be more susceptible to an out-of-band interference environment.

Since the IEMCAP models do not account for these phenomena, they could predict an interference situation where one does not exist, or worse, they could predict compatibility when an interference situation exists.

The model format of IEMCAP will allow system models to include filters. Therefore, a filter, representing antenna and RF cable frequency dependence, could be added to a model of an RF system. However, this approach results in a system model which does not represent the actual physical system, hence reducing it's effectiveness in a data base role. Addition of antenna and RF cable frequency dependent models, if included in IEMCAP, would not be accurate for all system geometry. An IEMCAP user should, however, be allowed the flexibility of specifying the antenna and RF cable frequency dependence characteristics if they are known. The models would then be as accurate as possible and they would provide a complete data base.

In addition to allowing the IEMCAP user to input antenna and rf cable frequency dependence, the IEMCAP program should contain models which could be used

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optionally to calculate antenna frequency dependent gains. Those models would be based on both analytical predicitons and test data. Methods of accomplishing this are contained in proposal D180-24888-1 to RFP F30602-78-R-0352.

3.3.4.1.4 Antenna-to-Wire and Field-to-Wire

Both the antenna-to-wire and field-to-wire coupling models are necessary capabilities of IEMCAP since antenna-to-wire and field-to-wire coupling problems must be analyzed at a system level. RF interference pickup on exposed wires, due to radiation from antennas, will likely cause problems for circuits that exhibit a nonlinear response at RF frequencies.

It is not desireable, however, to use IEMCAP to predict RF susceptibility thresholds due to non-linear effects since it is a system level computer program. Circuit susceptibility at RF frequencies should be determined by a stand alone computer program, i.e., NCAP or Circus or circuit level test. The threshold could then be included in an IEMCAP model for system level analysis. It is therefore desireable to change the input requirements of IEMCAP to accept this data in both required and non-required frequency regions. IEMCAP could then be configured to predict antenna-to-wire and field-to-wire coupling problems for the majority of circuit types.

3.3.4.2 IEMCAP Additional Capabilities

3.3.4.2.1 Bundle-to-Bundle

Bundle-to-bundle coupling problems are rare in systems. If a bundle coupling problem does exist, the problem is likely to be associated with improper grounding and isolation. Such a problem would involve a common impedance path.

IEMCAP does not contain, within its data base, system grounding and system isolation information which would be necessary to verify primary and secondary isolation requirements of MIL-STD-1541. The addition of a bundle-to-bundle coupling algorithm to IEMCAP would require a major revision to the transfer algorithms and data base. In addition, the benefits of adding a bundle-to-bundle coupling capability to IEMCAP are not obvious.

3.3.4.2.2 Wire-to-Field, Wire-to-Antenna, and Antenna-to-Field

Wire-to-field and antenna-to-field coupling capabilities would be a desirable addition to the coupling capabilities of IEMCAP. A subsystem's unintentional radiated emissions are normally comprised of emissions radiated from wiring and antennas. Therefore, a wire-to-field and antenna-to-field coupling capability is required in order to characterize a subsystem's unintentional radiated emissions if test data is not available. These new capabilities would enable IEMCAP to define unintentional radiated emissions data for interface control documentation when two or more subsystems are integrated to form a system. The existing field-to-wire and field-to-antenna coupling model contained within IEMCAP can be used to characterize margins of safety with respect to a subsystem's radiated susceptibility threshold. Thus, with the addition of these two coupling models, IEMCAP could be used to develop the unintentional radiated emission and susceptibility data required for interface control documents.

This would be especially valuable where the interface between subsystem is defined as a plane where the subsystems interconnect, such as stages of a launch vehicle. Emitter models coupled with wire-to-field and antenna-to-field coupling models would then be used by each subsystem prime contractor to define each subsystems contribution to the environment at the interface plane. Conversely, susceptibility models coupled with IEMCAP's field-to-wire and field-to-antenna coupling models would be used to assess the EMISMs between each subsystems susceptibility threshold and the environment at the interface. The calculated field levels could also be compared to radiated susceptibility levels which have been determined by test. This approach allows interface EMISM determinations by each subsystem prime contractor without a detailed knowldege of the subsystem on the other side of the interface.

Additionally, a wire-to-antenna coupling capability should be added to IEMCAP. This capability would be usefull in predicting interference between high frequency circuits and low frequency communication equipment, particularly where harmonics of digital circuitry, such as clocks, could interfere with airborne RF systems, a problem not unknown. The new wire-to-antenna coupling capability, used in conjunction with existing antenna-to-wire, wire-to-wire, and antenna-to-antenna coupling capabilities of IEMCAP, could be used to determine safety margins between unintentional radiated emissions and radiated susceptibility for subsystem integration.

3.3.4.2.3 Bulkhead Penetrations and Breakout Boxes

The possibility of modifying IEMCAP to account for breakout boxes and bulkhead penetrations in coupling calculations was also addressed in this study. No evidence was found which indicated that breakout boxes or bulkhead penetrations could not be included as part of an IEMCAP model by using the capabilities current found in IEMCAP, providing a very worst case representation is acceptable.

It was noted that segments of wires routed through bulkhead penetrations or breakout boxes may be exposed to different environments due to variations in shielding effectiveness. However, since the IEMCAP models allow wires to be routed through multiple compartments (via the bundle segment card) and since apertures can be included in the model to expose only certain portions of the wire segments, no special consideration of bulkhead penetrations or breakout boxes are required. However, if the wiring models were modified to allow the program user to specify shielding configurations for each bundle segment, this would result in more accurate coupling algorithms and a more complete cable data base.

3.3.5 Conclusions

a. Use of IEMCAP results in a uniform method of assembling a data base and provides a logical task flow for system EMC analysis. Assembling such a data base is necessary for the support of any EMC analysis.

b. IEMCAP analysis provides the analyst with a detailed knowledge of the system being analyzed and may result in identification of functional incompatibilities as well as EM incompatibilities.

c. IEMCAP may be used as a tool to reduce the need for system EMC tests, but as currently configured, is not an effective design aid or specification generator.

d. While use of IEMCAP does result in certain benefits such as those listed above, incorporation of the changes proposed in this document would make the program more desirable for use than other available analysis tools.

e. Efforts to either upgrade IEMCAP or develop a new generation IAP should be continued since the potential cost benefits of reducing system test requirements, performing specification tailoring, and identifying EM incompatibilities are very high.

f. Where existing analysis programs are available to perform specific specialized analysis tasks (particularly those difficult to solve using the IEMCAP analysis approach), it is not cost-effective or desirable to update IEMCAP to duplicate the effort. For example, many programs exist which compute exact solutions of circuit voltages and currents (within computer precision). The accuracy of this type of analysis is limited only by the ability of the programmer to produce an accurate model of the circuits being analyzed. This analysis approach can be used efficiently to perform EMC analyses such as power bus compatibility assessments. Typically, a power bus analysis must account for power line series inductance, varying load impedances, and switching transients which are more easily evaluated using a conventional time domain analysis approach. IEMCAP is not configured to analyze these effects and modifying IEMCAP to perform this analysis is a duplication of effort which would make IEMCAP unnecessarily cumbersome.

3.3.6 Recommendations

a. A study effort should be initiated which will determine IEMCAP model equivalents of generic circuit types and will verify model accuracy with respect to all emission/susceptibility modes. The study effort will result in the development of a user's manual annex which will aid the IEMCAP user in modeling and analyzing generic circuit types and will also help the user interpret IEMCAP results.

b. IEMCAP software and user's manuals should be modified to make input data units consistent with the units of common EMC data (i.e., MIL-STD-461).

c. IEMCAP maximum data base (model size) limitations, such as number of ports per equipment, need to be revised to allow for the analysis of larger systems per run. Multiple runs do not resolve program size limitations since all emitters need to be taken into account when evaluating receptor integrated margins. The model size must be consistent with the data base requirements of the program user. The thousands of ports in a typical system can be characterized by a fractional number of ports in a system model. However, the model must include sufficient information

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to be able to decipher which ports in the system are represented by each port in the system model.

d. The IEMCAP output needs to be revised to include a plot/graph format and a detailed transfer function breakdown.

e. Case-to-case and field-to-case coupling models in IEMCAP should be deleted.

f. IEMCAP should be modified to allow the program user to specify antenna and RF cable frequency dependent characteristics if they are known.

g. Input requirements for IEMCAP should be changed to allow specification of circuit non-linear responses at RF frequencies for antenna-to-wire and field-to-wire calculations.

h. IEMCAP should not be updated to analyze bundle-to-bundle coupling.

i. Wire-to-field, wire-to-antenna, and antenna-to-field coupling capabilities should be added to IEMCAP as supporting analysis for system integration.

j. IEMCAP does not need to be updated in order to account for bulkhead penetrations and breakout boxes.

4.0 CONCLUSIONS

4.1 Hardware Design

There are two approaches to the EMC design of a hardware system; a low risk program can be run which may penalize the system; or, a controlled risk program can be run which optimizes performance requirements and program constraints. As an example, consider the ways of implementing a binary interface signal; relays, transformers, optoisolators, differential line drivers, and single ended IC logic are possible choices. These methods are listed in an ascending order of EMC risk because of susceptibility characteristics; they are listed in descending order of system penalties such as size, weight, volume, power source, etc. Assuming the relays, transformers, and optoisolators are eventually eliminated because their data processing rates are too slow, this leaves only the line driver and single ended IC to be considered. The dual line driver's high common mode rejection ratio provides an advantage over the single ended IC, but this should not exclude the latter from further consideration. The dual line driver requires two signal lines and a return line (which can be shared with other circuits); the single ended IC requires only one signal line and a return line. Thus, for each IC that is used in place of a dual line driver, one wire and two connector pins are eliminated; this reduces weight, cable and connector size, and also increases reliability. Since decisions of this nature must be made early in the program when subsystem and system interface functions are being determined, the line driver is typically chosen because it has a low susceptibility to interference. However, if an analytical means or a reference data base was available, the controlled risk IC may have been selected which would effect accompanying system advantages. An EMC-IAP must support trade studies illustrated by this example as well as shielding, suppression, filtering, grounding, coupling, etc. The availability of codes suggests that the IAP should be computerized; however, the codes' scope, accuracy, and capacity have yet to eliminate the need for experience, judgement, and manual analysis, particularly for small scale or lower budget systems.

4.2 Test Methods

A susceptibility test philosophy was adopted in MIL-STD-461B that susceptibility tests would be performed to the test instrumentation limits or to the UUT malfunction threshold. Presumably, this approach was adopted for two reasons: (1) Prior susceptibility tests were not stringent enough to ferret out the type of problem that systems could experience; and, (2) many, if not the majority of susceptibility problems, are not normal

mode problems, i.e., they do not occur in a manner predictable by linear analysis methods. In either case, the susceptibility characteristics are necessary to evaluate the S:C:R relationship in which the source and coupling aspects can reasonably be measured, estimated, or computed. Without abnormal mode susceptibility data, the accuracy and completeness of EMC predictions is, and will remain, questionable.

Several MIL-STD-461B test changes were recommend herein, without specifying test limits which were noted by TBD (to be determined). The intent of this expression is that the actual values will have to be based on the characteristics of the system's power source, load, and distribution system; this is an extension of the tailoring aspect of MIL-STD-461B. Tailoring, as interpreted herein, is strictly a prime contractor responsibility to be used to establish specified tests, test methods, and test limits based on the needs of the system. Success of the tailoring approach primarily depends on: the understanding and communication between the procuring agency and the prime contractor , and the prime contractor's ability to implement a tailoring program.

A better susceptibility test is needed for MIL-STD-461B than the 200 v/m RS03 test. Incident radiation on UUT test cables will overexpose some wires and underexpose others because of the geometry of the test set-up. A device could be fitted over a UUT interface cable, provide a stripline the length of the cable on diametrically opposite sides, and be driven by a controlled signal generator is an alternative to antenna radiation coupling. The device would generate a magnetic field by placing a termination at the far end from the generator, an electric field by leaving the far end open, and in phase electric and magnetic fields by termination in a characteristic impedance.

MIL-E-6051 test methods are unstructured and should remain that way. Mechanical and electrical variations among systems discourage attempts at MIL-E-6051 test standardization.

4.3 Specification Changes

Other than a general updating no changes are recommended for MIL-E-6051.

Subsequent to the contract award for this task, MIL-STD-461B was released and scheduled to replace MIL-STD-461A. Revision B contained several changes deemed appropriate to better support system level tests.

a. A tailoring requirement was established which allow subsystem test requirements and limits to be based on system needs.

b. A requirement was established to perform susceptibility tests to the threshold or test instrumentation limits; this is a "loose" requirement but is a step in the proper direction as thresholds are mandatory for prediction purposes.

c. The limit exemption was removed on required spectra and this is deemed appropriate; each S:C:R parameter must be subject to individual or collective controls.

d. Some emission tests were deleted and one was added.

Recommended changes presented in Section 3.2.1 for MIL-STD-461B are as follows:

Modify - CE01, CE07, CS01, RE02, RS02, RS03
Add - CSXX
Study for consolidation or elimination - CE06, CS03, CS04, CS05, CS07, RE03
Eliminate - CS02, CS06

4.4 IEMCAP

Detailed conclusions and recommendations for IEMCAP are presented in Sections 3.3.5 and 3.3.6, respectively. The following additional comments are in relationship to the test specifications and analyses.

a. IEMCAP is based on MIL-STD-461A. The impact which the elimination of the required spectra from MIL-STD-461B may have on the code was not evaluated; nor was MIL-STD-461B's floating susceptibility limit, by virtue of the new over-test requirement, evaluated.

b. A principal function of IEMCAP is to establish MIL-STD-461 limits compatible with MIL-E-6051 requirements. Not withstanding the caution implied by MIL-E-6051 regarding MIL-STD-461 (see Section 2.2), MIL-E-6051 requires finite dB values for safety margins, i.e., 0,1,2,3,...6,20, etc. It is not apparent that IEMCAP will accommodate these small incremental values.

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c. The inability of IEMCAP to handle problems presented by the circuit types illustrated in Figures 2.2 and 2.3 as well as other types will require that they be analyzed by other means.

4.5 Data Base

In developing a test data base for analysis purposes commonality of measurement parameters is desireable between MIL-STD-461 and MIL-STD-6051 Testing efforts. The majority of MIL-E-6051 measurements are usually to be made using an oscilloscope, voltmeter or spectrum analyzer. These different voltage dimensions will comprise the main data base. This will also be true after the system has been delivered to the customer. The majority of MIL-STD-461 measurements are unique, using current probes, antennae, and networks based on a 50 ohm instrumentation. Thus, a one-to-one comparisons between MIL-E-6051 test data and MIL-STD-461 test data is very difficult. Since MIL-STD-461 has developed a quasi conversion means for the instrumentation specified and MIL-E-6051 measurement methods are more universal, it appears better to continue converting MIL-STD-461's hybrid data rather than adapt it's parameters to MIL-E-6051 and general system measurements.

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5.0 RECOMMENDATIONS

Several issues not covered elsewhere in this report which are recommended for further study are: Microelectronics Susceptibility Characterization, Cable Injection Scheme, Field Service Data Collection/Analysis Program, and Code Certification Program.

5.1 Microelectronic Susceptibility Characterization

A pulsed test method is needed for digital, microelectronics which can be used for both diag..ostic and validation tests. The method should be standardized to the extent that users can interpret the results for general applications on small, medium, and large scale microelectronic products. All interference leads should be addressed by the test.

5.2 Cable Injection Schemes

RF susceptibility tests usually rely on a fixed antenna-to-UUT/cable relationship. This method should be augmented by a direct injection scheme which can be correlated to free field conditions and offers the following improvements to existing methods, (a) be used in any laboratory set-up, (b) restricts the EM field to the region of interest, and (c) exceeds or satisfies the 200 v/m criterion of MIL-STD-461B without causing a health-hazard concern.

5.3 Field Problem F. :d-Back Plan

EMC control presently includes design requirements to achieve compatibility of equipment and environments, and, tests per MIL-STD-461 and MIL-E-6051 to validate the design. However, this approach is frequently insufficient and field EMC problems occur. A plan should exist whereby a contractor that has MIL-E-6051 responsibility also has a responsibility through a sustaining engineering or logistics contract to provide a specialized EMC diagnostic service that covers field operations and EMI problems.

5.4 Code Certification

The state-of-the-art for EMC is becoming ever more dependent on computer analysis aid for the initial design, test and modification of military hardware systems. Computer analysis programs created for these purposes are subject to inherent errors, incompleteness and misapplication that can lead to consequences of the same nature. A certification program is needed which validates the codes accuracy and applicability on actual hardware systems.

APPENDIX A

A-1.0   PORT IMPEDANCE

The impedance of equipment ports can be measured using EMI test facilities. A general outline of the procedures used in determining port impedance (PZ) and the potential limitations of the measurements is presented below. In some instances, specific instrumentation is recommended.

A-1.1   PRIMARY POWER INPUT PORTS

The impedance at the input power terminals of a piece of equipment can be determined from data acquired during MIL-STD-461A CSO1 and CSO2 testing. The PZ can be determined by measuring the current and voltage levels of the susceptibility signals at the input power terminals. The PZ is then obtained by dividing the voltage by the current for all test frequencies. Measurement and preliminary processing of the raw data can be greatly facilitated by the use of an HP8568A spectrum analyzer. The magnitude of the current produced by the susceptibility test signal can be measured using the spectrum analyzer and Stoddart 91197-1 and 91550-1 current probes, or equivalent. The susceptibility test signal voltage level can be measured using the same spectrum analyzer and an HP1120A active probe which is powered by the spectrum analyzer. Figures A-1A and A-1B illustrate equipment interconnections for aquisition of this data. Using the trace storage and arithmetic capabilities of the spectrum analyzer, the current (in dBuA) can be subtracted from the voltage (in dBuV), yielding the raw impedance data. The raw impedance data can then be manually corrected as required. It should be noted that with a suitable controller, such as an HP9825 desktop computer, the data processing can be performed automatically. The current and voltage data cannot be acquired simultaneously, however, because of the mechanization of the spectrum analyzer.   They must be acquired on successive scans for a given set of spectrum analyzer settings.

A-1.2   SIGNAL AND CONTROL PORTS

The process of acquiring the current and voltage data for determination of signal and control PZ is essentially the same as the process used for the power port. The difference between the two procedures is in the method of coupling the susceptibility
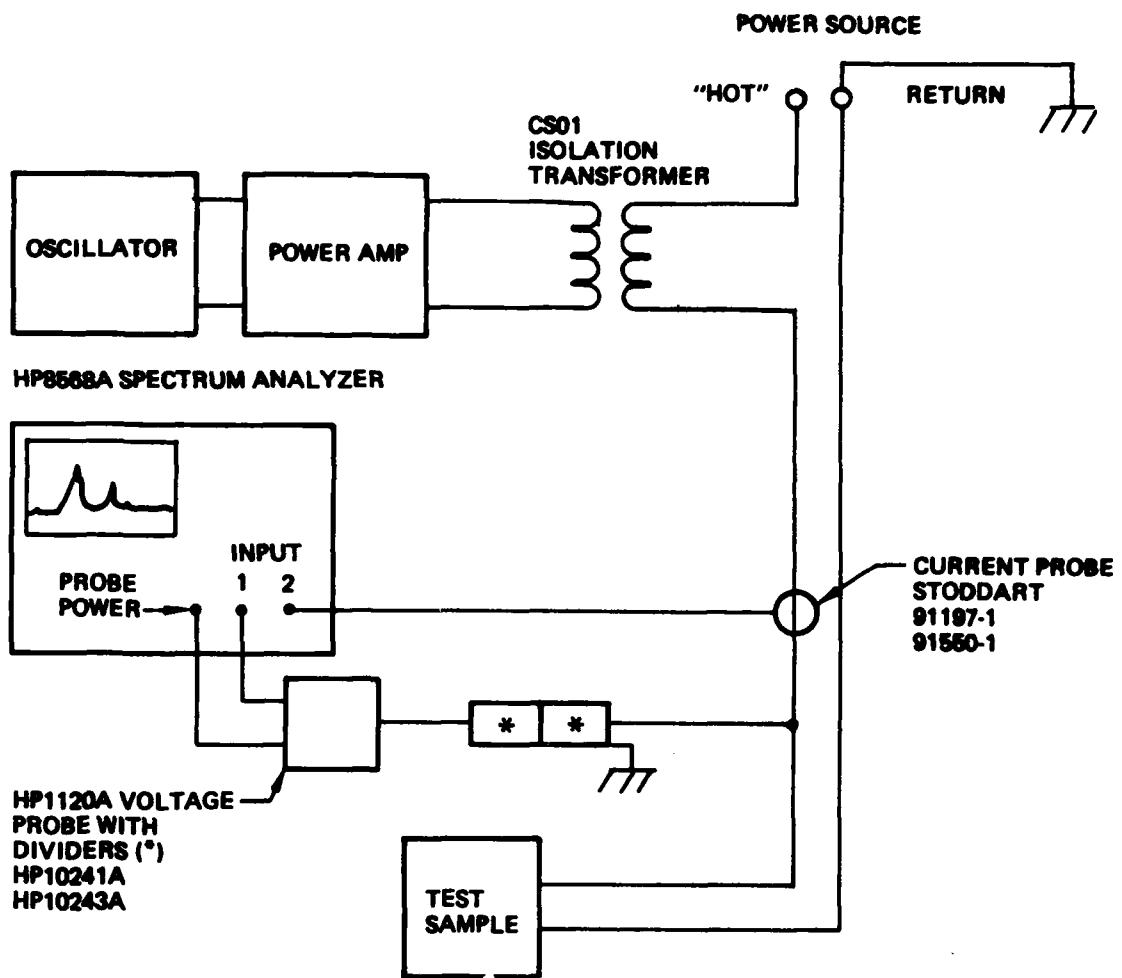
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Figure 1A: Test Set-Up, Power Port Impedance Measurement 0-50 kHz

85

SIGNAL
SOURCE

CAPACITOR IMPEDANCE
5 OHMS OR LESS AT
SIGNAL FREQUENCY

CURRENT PROBE
STODDART
91197 - 1
91550 - 1

INDUCTOR MAY BE
REQUIRED TO
REDUCE LOADING
OF POWER SOURCE
ON SIGNAL SOURCE

POWER
SOURCE

TEST
SAMPLE

HP8568A SPECTRUM ANALYZER

INPUT

1   2

PROBE
POWER

HP1120A VOLTAGE
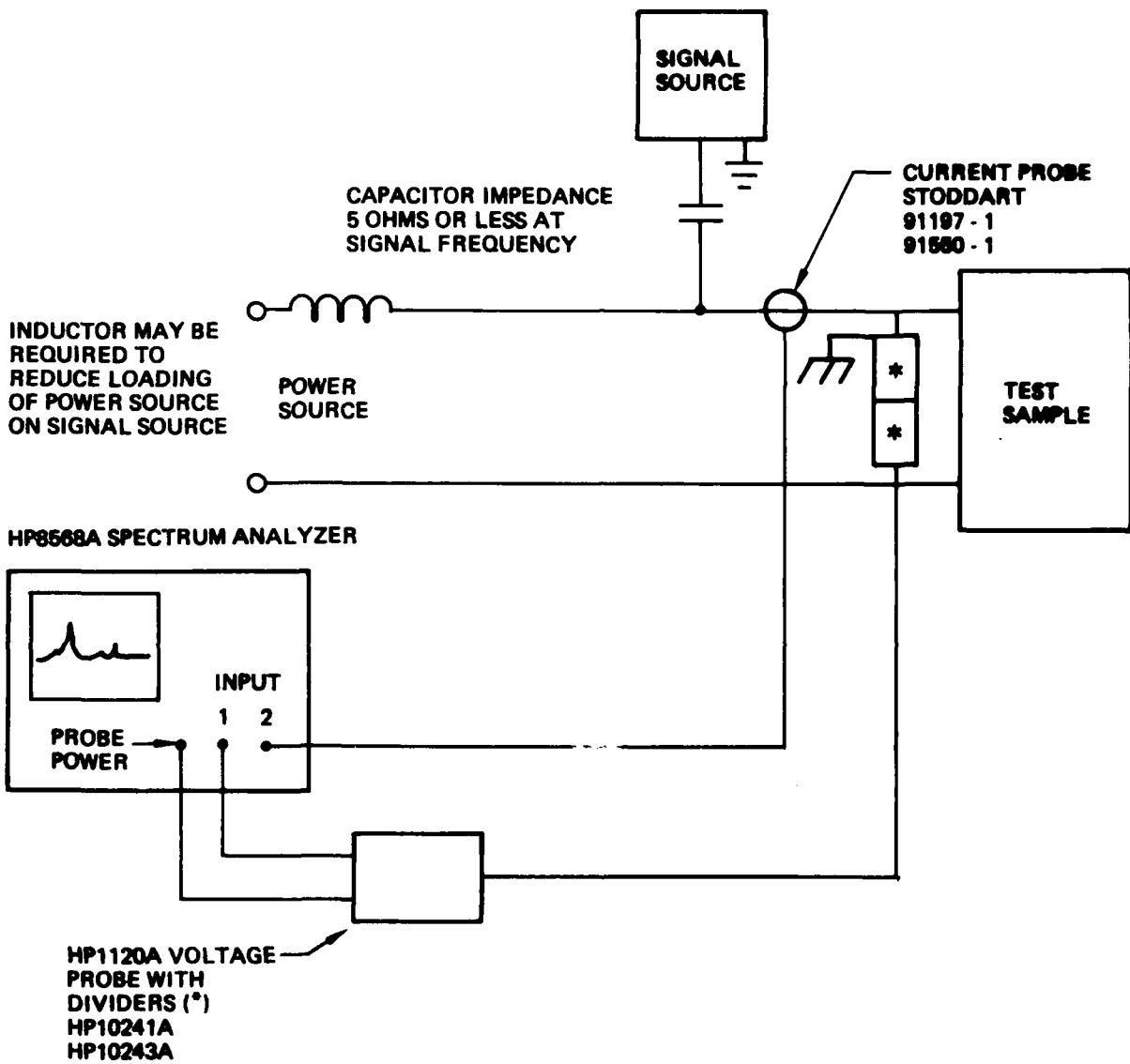PROBE WITH
DIVIDERS (*)
HP10241A
HP10243A

Figure 1B: Test Set-Up, Power Port Impedance Measurement 50 kHz - 400 MHz

test signal into the associated circuit. The susceptibility test signal can be coupled into the associated signal and control cables with the same current probes that were used for the power port measurements. In certain circumstances, it may be possible to use the CSO1 and CSO2 test signal injection techniques. Since the PZ should be determined for all associated circuit states, additional support equipment will be required to provide the necessary driving signals. Figure A-2 illustrates the equipment interconnection for aquisition of this data for a typical digital circuit. Observe that the differential and common mode impedance can be obtained merely by changing the location of the current probe used to induce and measure the level of the stimulus current.

This type of test is not meaningful for co-axial ports, because the shielding effectiveness of co-axial cables is so high that only energy originating at the end of the cable has the potential for generating an undesirable response in the associated equipment. Data describing the response of receivers to undesired signals is acquired during MIL-STD-461 CSO3, CS04, and CS05 testing, while transmitter output intermodulation data is acquired during performance testing.

A-1.3   MEASUREMENT LIMITATIONS

Although limitations will be encountered in the performance of the measurements described above, which are unique to specific equipment, three limiting factors which will be encountered in all cases are the electromagnetic environment of the equipment, power limited EMI sources, and (parasitic) effects from uncontrolled parameters.

Since the measurements will be performed on equipment in operation, they will have to be performed in the presence of all of the intentional and unintentional equipment emissions. At the equipments power input terminal, the environment includes the fundamental, and harmonics, of the power frequency and higher frequency harmonics of the equipments timing and data signals. At signal and control ports, the environment will primarily consist of intentional signals which may be hard to measure due to a wide asynchronous bandwidth. Consequently, acquisition of the desired data may not be possible at the signal frequencies.

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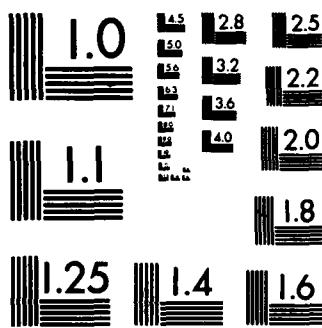
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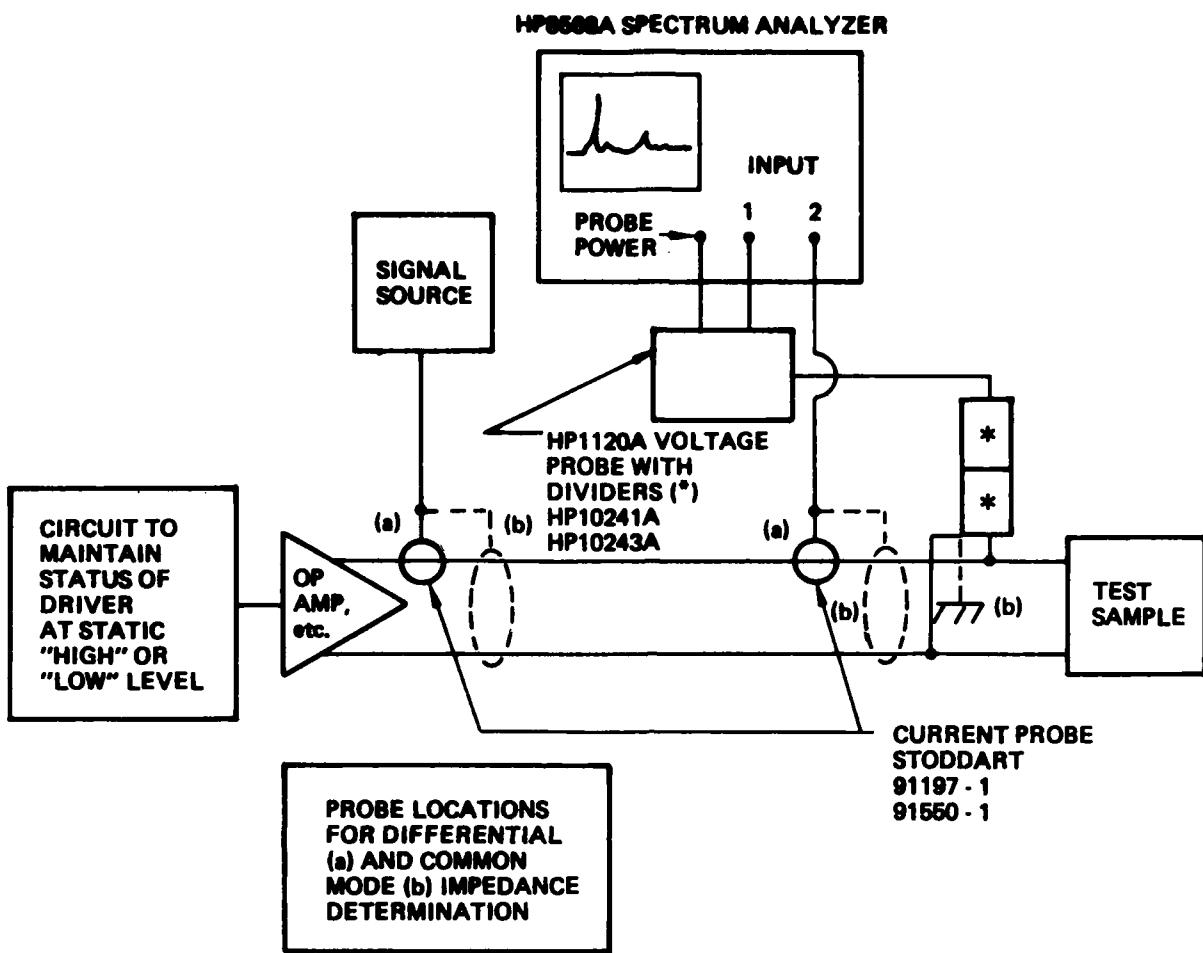
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Figure 2: Typical Test Set-Up to Determine Port Impedance for Digital Circuit

MIL-STD-461 specifies that if the required CS01 and CS02 susceptibility test signal cannot be developed across the test samples input power terminals, with a signal source of specified power, the equipment is deemed to meet the requirement. The test developed by The Boeing Company to simulate the coupling of RF energy from an onboard HF transmitter onto equipment signal and control lines, (B)CS09, also places similar conditions on the conduct of the test. These limitations are the result of recognition of two important facts: the existence of circuit resonances and power limited interference sources. Attempts to generate the MIL-STD-461 required suscep- tibility test signals at a test samples port at an associated resonant frequency may result in damage to, or destruction of, the test sample or test equipment. The second reason for the power limitation of susceptibility test signal sources is that the corres- ponding system signal source is also power limited. These limitations should be considered when using the resultant data in a subsequent system analysis.

The validity of performing the above measurements on a limited number of samples of a given type of equipment will be directly related to the effects from uncontrollable or slightly variable parameters. Most of these effects are due to variations in the location of wiring, lead lengths to discrete components, and "pig-tail" shield terminations. Occasionally, these effects are due to variations in an important characteristic of a component at frequencies far beyond its design band frequency range. Therefore, the number of samples of an equipment type test should be large enough to provide statistically meaningful results.

A-2.0 ELECTRIC POWER SYSTEM IMPEDANCE

A detailed knowledge of an electric power subsystem (EPS) is required to determine the effect of power line conducted EMI on the overall system. In the following discussion it is assumed that EMI generated by system equipment does not result in degraded EPS performance. Neglecting other effects, the effect of EMI generated by one piece of equipment upon another piece of equipment in a system depends upon the impedance of the EPS at the frequency of the EMI. The impedance seen at the input power terminals of eqiupment is a combination of the impedance of the power source, other equipment powered by the EPS, and the power lines themselves. The relative magnitude and frequency range of the associated impedances are described below.

1. Power Source Impedance

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At the fundamental and low order harmonic frequencies of an AC power source, the impedance consists of a very low resistance and a very low reactance which is usually inductive. For a DC power source, the impedance may have a large reactive component.

2.   Equipment Primary Power Input Port Impedance

From the fundamental frequency of an AC EPS (or zero HZ for a DC EPS) to the megahertz frequency range, the effect of the electronic equipment powered by the EPS is observed. At the fundamental frequency, or zero HZ, for an AC or DC EPS respectively, the impedance is almost totally resistive with a tendency towards a slightly laging power factor due to the power conversion and regulation process. Occassionally, the EMI filters in equipment will result in a leading power factor. As freqeuncy increases, the magnitude of the reactive component will either increase or decrease depending on the EMI filter input-inductor or capacitor. Specific equipment, such as a motor, may have a significantly leading or laging power factor.

3.   Power Wiring

The third part of the impedance seen at the input power terminals consists of the self inductance and capacitance values of the EPS interconnecting wiring. Until the length of the wire to the power source, or other equipment, approaches a significant portion of a wavelength, these values should be considered as lumped parameters. In comparison to the power source or equipment impedances, the equivalent impedance of the wiring is inconseqential. However, for the purposes of consideration of fast rise time transient propagation, the inductance and capacitance parameters of the wiring should be considered as distributed parameters.

Therefore, the using equipment impedance looking back toward the power source starts out as a very low value at low frequencies, rising as frequency increases to the characteristic impedance of the wiring to which the equipment is connected. In between the two extremes the value of the impedance will vary depending on the values of the components in EMI filters of other equipment. Additionally, depending on the construction of the EMI filters and their components, inductors may appear as

capacitors due to interwiring capacitance, and capacitors may appear as inductors due to lead reactance.

A-2.2   IMPEDANCE MEASUREMENTS

The impedance of the power source, equipment input power ports, and associated interconnecting wiring can be determined by test. An outline of the procedures to measure and determine the impedance of a power source and the EPS interconnecting wiring is presented below. Procedures for measuring the impedance at an equipment's power input port is described in section A-1.1.

EPS designers generally determine the impedance of the power source at the frequency of operation as the basis for power budget and calculations of voltage regulation. The impedance of the power source at harmonic frequencies can be determined by measuring the harmonic current and voltage levels while the power source is loaded by a purely resistive load bank. These current and voltage levels can be measured with a spectrum analyzer, current and voltage probes as described in section A-1.0. At higher frequencies, the impedance may be determined by injecting a test signal and measuring the level of the current and voltage of the injected signal, as also described in the section on port impedance measurement.

Measurement of the self inductance and capacitance of the actual wiring of an EPS is straight-forward. The inductance of any wire segment can be determined by connecting one end of the wire segment to the system ground plane and then measuring the inductance from the other end at a suitably low frequency. The capacitance of the wire segment can be similarly measured by floating one end of the wire segment. The more variable the height of the wire segment over the ground plane, the more the resulting values will be average values.

The impact of the EPS impedance on the propagation of EMI generated by one equipment is that all lower frequency components will be seen by all equipment at the generated level. The higher frequency EMI components will arrive at the other equipment at virtually any amplitude due to standing wave effects.

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